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Environmental Assessment Data Base for Coal Liquefaction Technology: Volume I Systems for 14 Liquefaction Processes

Hittman Associates, Inc, Columbia, MD

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Volume I. Systems for 14 Liquefaction Processes

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16. ABSTRACT The two-volume report, prepared as part of an overall environmental assessment (EA) program for the technology involved in the conversion of coal to clean liquid fuels, and the Standards of Practice Manual for the Solvent Refined Coal Liquefaction Process (EPA-600/7-78-091) represent the current data base for the EA of coal liquefaction technology. This volume summarizes pertinent information about 14 prominent coal liquefaction systems now being developed. For each system, it includes a brief description, a flow diagram, and a list of materials entering and leaving the system. Potential applicable control techniques are described generally, along with the current status and development plans for the 14 systems. The main conclusion from this volume is that these processes are not environmentally defined in the published literature; however, there is some indication that current development plans may help to correct this situation. Volume II is an environmental characterization of three of four selected coal liquefaction systems: Synthoil, H-Coal, and Exxon Donor Solvent.

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by

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ABSTRACT

This report was prepared as part of an overall environmental assessment program for the technology involved in the conversion of coal to clean liquid fuels. The program is being directed by the Fuel Process Branch of the Environmental Assessment and Control Division of the Industrial Environmental Research Laboratory at Research Triangle Park, North Carolina. The two volumes of this report plus the Standards of Practice Manual for the Solvent Refined Coal Liquefaction Process (EPA-600/7-78-091) represent the current data base for the environmental assessment of coal liquefaction technology.

In general, liquefaction operations begin with pretreatment of the feed. Feed must be reduced to the required coal particle size, and either dried or formed into a slurry by mixing with a process-derived slurry. Thus prepared the feed enters the liquefaction operation where the addition of hydrogen to carbon occurs along with a dissociation of the components in the coal. These components are then separated from the liquefaction products through a variety of operations. The resulting products and by-products are purified, upgraded, and refined. By means of a modular concept, the characteristics of process input and output streams including wastes are displayed.

Volume I, "Systems for Fourteen Liquefaction Processes," provides a summary of pertinent information about prominent coal liquefaction systems now under development. For each system it includes a brief description, a flow diagram, and

a list of the materials entering and leaving the system. The processes required to produce clean liquid fuels from coal are divided into discrete operations. Each of these operations is then further divided into discrete modules, with each module having a defined function, identifiable raw materials, products, and discharge streams. A general discussion of potential applicable control techniques is presented along with the current status and development plans for the fourteen coal liquefaction systems.

The main conclusion reached from the preparation of Volume I is that these processes are not environmentally defined in the published literature, however, there is some indication that current development plans may help to correct this situation. Hittman Associates, Inc., will be investigating ways to help fill in the missing information through contacts with others and through the development of test plans.

Volume II, "Detailed Discussion of Synthoil, H-Coal and Exxon Donor Solvent Processes," is an environmental characterization report covering three of four selected coal liquefaction systems. It provides documentation and evaluation of existing environmentally significant data. Environmental characterization includes an integrated multimedia assessment of the discharges to the environment from conceptualized 7,950 m^3 (50 kbbl) per day systems. Estimations are given for the raw waste streams, treatment/control processes, treated waste stream discharges, and the effects of these discharges on the environment.

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Mr. Dewey Dykstra, Senior Chemical Engineer

INTRODUCTION

Volume I of this document presents a summary of the technology and environmental factors associated with the production of liquid fuels from coal. It provides a broad picture of the liquefaction program, identifies the processes which constitute program elements and areas needing study, and proposes a preliminary modular approach for later work.

Information has been included for as many specific processes as data permitted. The approach taken has been to make the liquefaction technology coverage general rather than to attempt detailed descriptions. Detailed descriptions for selected processes have been developed in Volume II and in the Standards of Practice Manual for Solvent Refined Coal, EPA-600/7-78-091.

EXECUTIVE SUMMARY

In its broadest sense, the coal liquefaction program includes Federal, state, and private efforts to develop means of producing liquid hydrocarbons from coal. Projects are being sponsored by each of these segments. By far the largest number of projects are funded by DOE or jointly by DOE and private industry. These are also the most publicized in terms of availability of technical, economic, and programmatic information. For these reasons, the primary concern of this document is with DOE supported projects, though not to the total exclusion of other efforts.

Near-term objectives of the DOE coal liquefaction program appear to be: to develop commercialization of potential second generation technology for producing boiler fuel, heating oil, gasoline, and chemical feed stocks; to provide technology needed for commercial liquefaction via first generation technology; and to provide basic research and development in support of third generation processes. Long-term objectives are to achieve commercialization of second generation technology and to demonstrate and ultimately commercialize third generation technology.

These objectives are being met by project support in each element of the program. The program elements include hydroliquefaction, pyrolysis, indirect hydrogenation, and supporting technologies. For the purposes of this summary document the technology categories used are hydrogenation, pyrolysis and hydrocarbonization, and extraction and catalytic synthesis. There is a limited number of advanced processes at this time. In the projects which have been active, emphasis has been adjusted to conform with the results of research and development studies and of changing needs.

The hydrogenation process is the most advanced. Two SRC pilot plants are successfully operating. A full scale test of the combustion characteristics of solvent refined coal (SRC-I) was conducted in the spring of 1977. The H-Coal process, also in the hydrogenation category, is nearing completion of the pilot plant construction stage. When operational this facility will be the largest liquefaction plant in the United States. The Exxon Donor Solvent (EDS) process is planned for piloting in the near-term. A 227-metric ton (250-ton) per day pilot plant is to be built at Baytown, Texas, as a joint government-industry project. The schedule plans for operation to begin in FY 80. It is projected as a major developmental effort.

Pyrolysis and hydrocarbonization projects include the two primary efforts of the Char-Oil-Energy-Development (COED) and Coalcon processes. COED has progressed successfully through the pilot plant and work on this process has been terminated; however, the developers are pursuing related efforts. The Coalcon process developers faced with the problems of escalating costs as well as technical problems, have shelved plans for construction of a pilot plant. All processes in this category will have the disadvantage of comparatively low thermal efficiency.

The Supercritical Gas Extraction process has not been developed beyond the laboratory stage. Catalytic synthesis includes the Fischer-Tropsch process which is currently used in South Africa to produce gasoline and chemical feedstocks.

Although significant technical differences between the liquefaction processes do exist, many of the individual unit and processing steps are common to several systems. To avoid the redundancy of studying these common areas in each system, a process modular concept is used. A process module is a representation of a process which is used to display input and output streams. Thus the operations in coal liquefaction technology; coal pretreatment, liquefaction, separation and purification each consist of a series of steps such as coal crushing, hydrogenation, filtration, and hydrotreating which can be represented by modules. Figure 1 displays this concept. Figure 1 also shows the auxiliary processes (such as oxygen generation and sulfur recovery) which are associated with coal liquefaction technology although they are incidental to the main functions involved in the transformation of raw materials into end products.

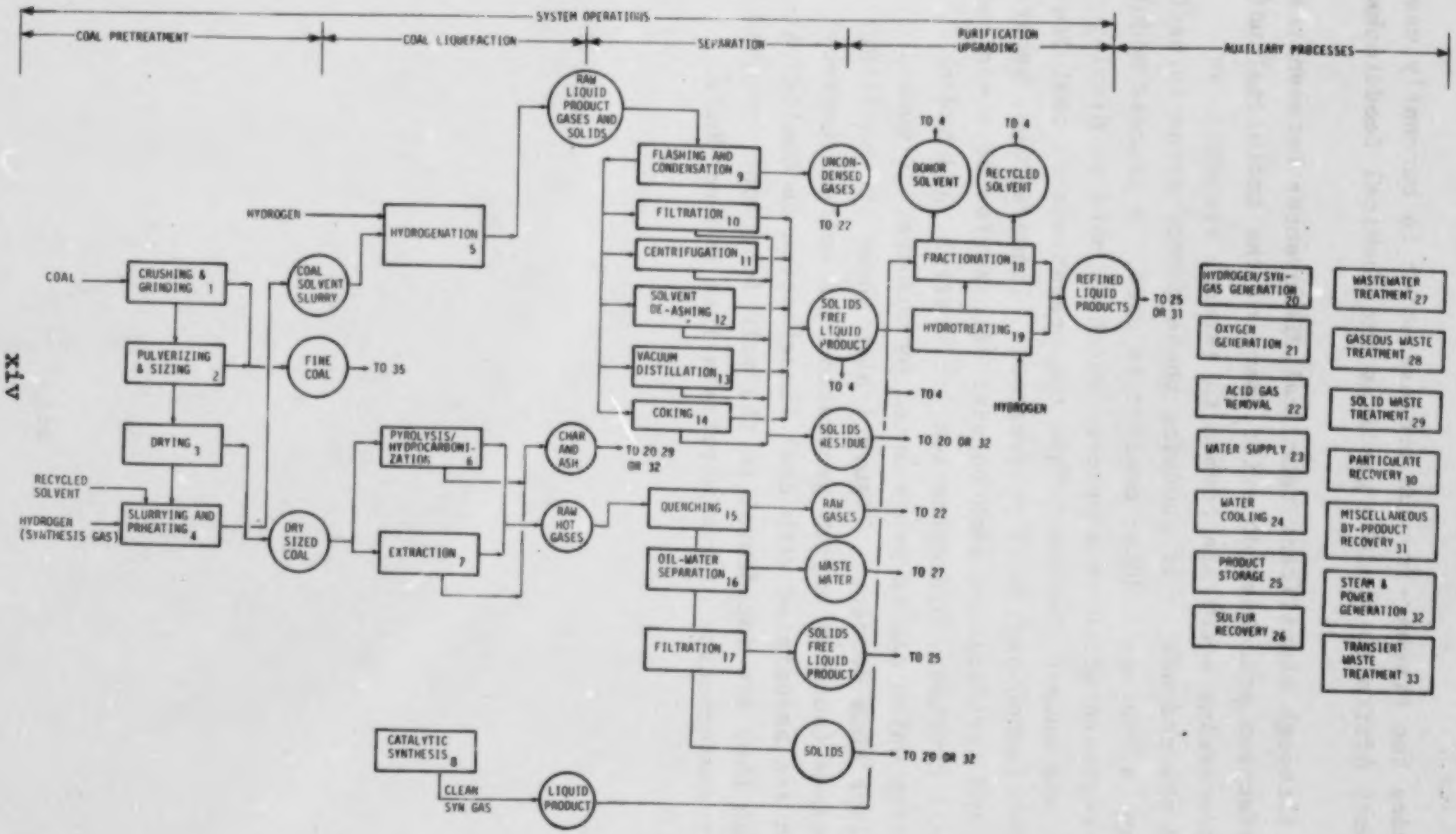
SYSTEM OPERATIONS
COAL PRETREATMENT
COAL LIQUEFACTION
SEPARATION
PURIFICATION UPGRADING
AUXILIARY PROCESSES
COAL
CRUSHING & GRINDING 1
PULVERIZING & SIZING 2
DRYING 3
RECYCLED SOLVENT
HYDROGEN (SYNTHESIS GAS)
SLURRYING AND PREHEATING 4
COAL SOLVENT SLURRY
FINE COAL
TO 35
DRY SIZED COAL
HYDROGEN
HYDROGENATION 5
PYROLYSIS/ HYDROCARBONIZATION 6
EXTRACTION 7
CATALYTIC SYNTHESIS 8
CLEAN SYN GAS
LIQUID PRODUCT
RAW LIQUID PRODUCT GASES AND SOLIDS
CHAR AND ASH
TO 20 29 OR 32
RAW HOT GASES
FLASHING AND CONDENSATION 9
FILTRATION 10
CENTRIFUGATION 11
SOLVENT DE-ASHING 12
VACUUM DISTILLATION 13
COKING 14
QUENCHING 15
OIL-WATER SEPARATION 16
FILTRATION 17
UNCONDENSED GASES
TO 27
SOLIDS FREE LIQUID PRODUCT
TO 4
SOLIDS RESIDUE
TO 20 OR 32
RAW GASES
TO 22
WASTE WATER
TO 27
SOLIDS FREE LIQUID PRODUCT
TO 25
SOLIDS
TO 20 OR 32
TO 4
TO 4
DONOR SOLVENT
TO 4
RECYCLED SOLVENT
FRACTIONATION 18
HYDROTREATING 19
HYDROGEN
REFINED LIQUID PRODUCTS
TO 25 OR 31
HYDROGEN/SYN-GAS GENERATION 20
OXYGEN GENERATION 21
ACID GAS REMOVAL 22
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Figure 1. Module diagram for coal liquefaction systems

SECTION 1

TECHNOLOGY CHARACTERISTICS

INTRODUCTION

Estimates of current petroleum reserves indicate a limited remaining life for useful production of fuels. This has generated renewed interest in technology for producing liquid hydrocarbons from coal, with the primary objective of producing clean liquid fuels. Coal liquefaction is not a new technology; it dates back to the early part of the twentieth century - the concept even earlier.

During the nineteen-twenties and thirties, extensive research into the hydrogenation of coal was performed in Germany. German interest in liquid fuels stemmed from the fact that the nation had extensive coal reserves but no domestic petroleum. The United States Department of the Interior conducted small scale feasibility studies of the German technology, but these efforts were abandoned when immense quantities of oil were discovered in east Texas in 1930.

In 1944, during the latter part of the second World War, interest in coal liquefaction in the United States was renewed. In that year the Synthetic Fuels Act provided sixty million dollars to fund studies through 1955. Another large oil discovery, this time in the Middle East, reduced interest in creating liquid fuels from coal.

With the advent of declining petroleum reserves, fewer new discoveries, escalation of prices, and real or induced shortages, coal liquefaction technology has once more assumed a major role as a potential solution to liquid fuel problems. Currently some twenty-odd processes are in various stages of development by industry and federal agencies.

In general, liquefaction processes offer several advantages over gasification of coal. The overall thermal efficiency is usually higher and process water requirements are reduced. Liquid fuels have a much higher energy density than fuel gases. Liquefaction processes operate under less severe temperature and pressure conditions than gasification processes. These advantages may tend to favor more rapid development and commercialization of new liquefaction than new gasification (1).

All liquefaction processes produce liquids by yielding a material having higher hydrogen content than coal. Hydrogen is present in coal at a level of about 5 percent. In high-Btu gas it is roughly 25 percent. Fuel oils contain 9 to 11 percent hydrogen and gasoline about 14 percent. Whether the required hydrogen increase is obtained by adding hydrogen to the coal components, or by stripping the hydrogen-rich components from the coal depends upon the particular process. The method used also affects the yield of liquid from the process.

The hydrogen increase is not completed in the initial reaction. Upgrading by hydrotreating is required to produce higher quality fuels. The initial crude liquid is suitable only for utility fuel. Hydrotreating is also necessary to reduce sulfur, nitrogen and oxygen content.

Varying amounts of carbon remain unreacted as a char, depending upon the process. In some systems, this char is used to generate hydrogen by the steam carbon reaction. Other processes produce such a high proportion of char that it must be considered by-product fuel.

In place of hydrogen, synthesis gas may be used in several processes. Synthesis gas is a mixture of hydrogen and carbon monoxide in varying proportions generated by the reaction of carbon with oxygen and steam.

For specific applications the ratio of hydrogen to carbon monoxide can be adjusted by the CO-shift reaction,

$$CO + H_2O \longrightarrow H_2 + CO_2.$$

If carried to completion, actually equilibrium, essentially pure hydrogen, except for impurities which may have been in the feed gas mixture, results after the carbon dioxide is removed.

A wide range of process conditions and configurations exist within the liquefaction technology. Descriptions of the more important processes are presented in the remainder of this section.

HYDROGENATION

Synthoil System

Background--

While much of the past research in liquefaction was directed towards making a substitute refinery feedstock, the Synthoil Process is one of the few specifically aimed at making a low sulfur fuel oil for the electric utility industry. The urgent need for such a fuel was emphasized by the shortage of petroleum in the heating season of 1973-1974. Many power plants are now fired with petroleum-derived fuel instead of coal because petroleum, which burns cleaner than coal, complies with greater ease to environmental regulations. An environmentally acceptable coal-derived Synthoil, therefore, could help release petroleum fuel oil for other uses (1).

The intent of the Synthoil Process development was to show that, under the right conditions, reaction of coal with hydrogen will promote desulfurization and minimize additional hydrogenation of the products from the primary liquefaction. Work on such a process was initiated by the United States Bureau of Mines at the Pittsburgh Energy Research Center in 1969. It has led to a process in which coal is liquefied and desulfurized in a single step by catalytic hydrotreatment in a highly turbulent, co-current, up-flow, packed-bed reactor. The initial work used a reactor with an internal diameter of 8 mm with daily feed rates of 22 kg of coal or 54 kg of slurry.

Experimental work was carried out on various coals including Pittsburgh, Indiana No. 5, Middle Kittanning, Ohio No. 6, and Kentucky coal. All of these types of coal were satisfactorily converted to low-sulfur fuel oil with no appreciable attrition of catalyst or loss of catalyst desulfurization activity. Other parameters investigated were hydrogen flow rate, coal content of feed slurry, recycling of product oil, and the effects of hydrogen sulfide on recycled gas. A larger bench-scale unit, 28 mm internal diameter and 4.42 m long, was operated at daily feed rates up to 181 kg of coal and 454 kg of slurry. Reactor pressure was varied from 14.7 to 29.4 MPa at temperatures up to 450°C.

The lower reactor pressure corresponded to lower yields, heating value, and hydrogen consumption. Sulfur and ash content of the low pressure oil were higher than those of the oil made at 29.7 MPa. Operation at the lower pressure is desirable provided an environmentally acceptable product can be made. A 9.1-metric ton per day process development unit (PDU) is under construction (2).

System Description--

Figure 2 is a flowsheet of the system. Coal feed for the Synthoil Process is prepared by drying and then grinding to 90 percent less than 250 μm or 65 percent less than 63 μm. The ground coal is thoroughly mixed with recycled product oil to form a paste or slurry containing about 40 percent coal and 60 percent oil. The slurry, together with recycled and makeup hydrogen, is preheated and then passed to the reaction zone. The reactor is packed with one-eighth inch pellets of a type of commercial catalyst used in desulfurizing petroleum derivatives. Under operating conditions described above, hydrogen liquefies the coal and simultaneously removes sulfur, oxygen, and nitrogen (3).

The major portion of the coal is hydrogenated to gas and oil which are separated by a pressure reduction. The oil stream containing Synthoil residue, and mineral matter is treated to separate the oil and solids. The oil is divided into two streams, one of which is returned to feed preparation and the other withdrawn as product. Residue and oil are separated; the oil is sent to product storage and the residue goes to the hydrogen production area. The gaseous mixture from the reaction contains unused hydrogen which can be recycled through the reactor. However, it also contains hydrogen sulfide and ammonia. These two contaminants are removed by absorption in the gas purification system. The hydrogen sulfide is sent to a sulfur recovery

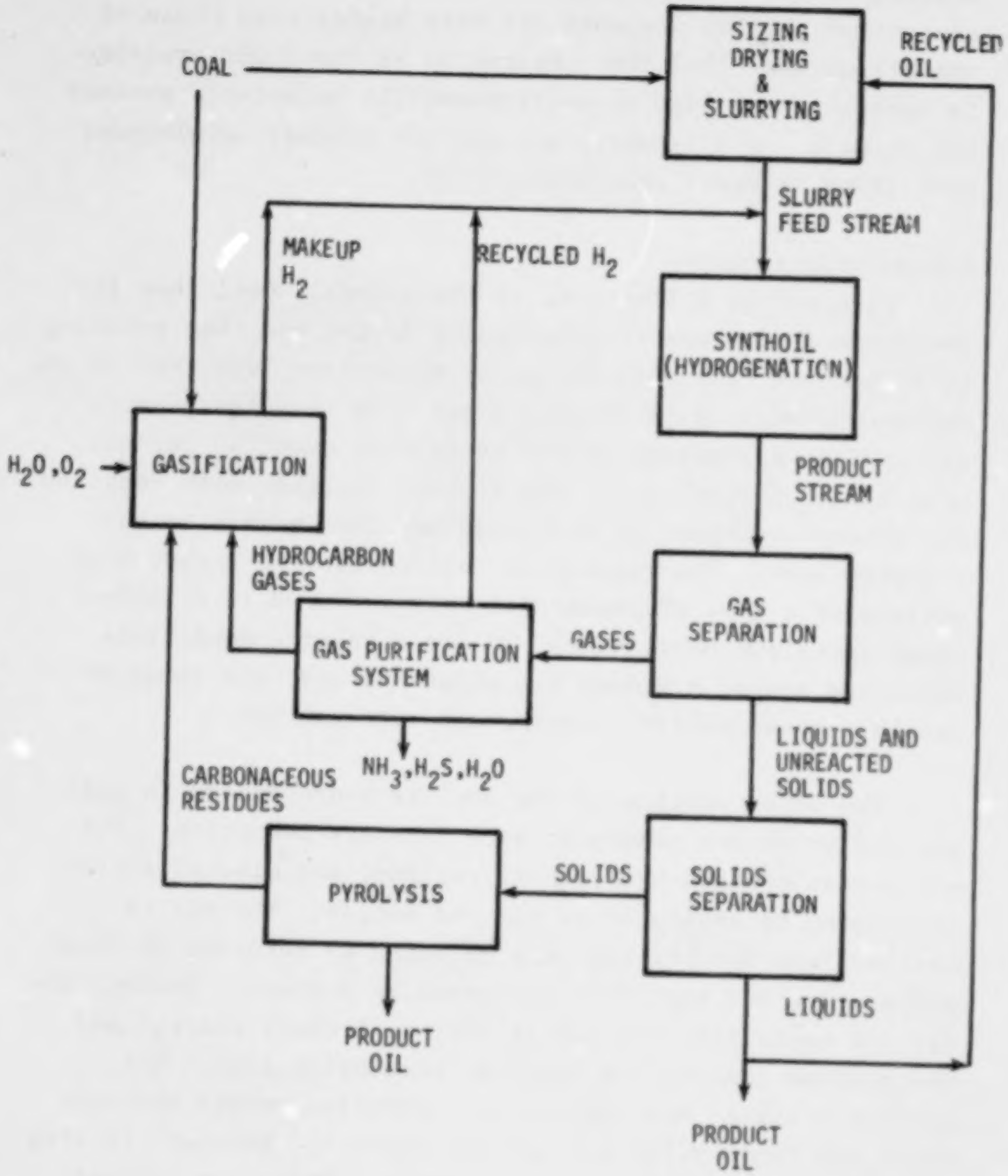

SIZING DRYING & SLURRYING
COAL
RECYCLED OIL
SLURRY FEED STREAM
MAKEUP H_2
RECYCLED H_2
SYNTHOIL (HYDROGENATION)
H_2O, O_2
GASIFICATION
PRODUCT STREAM
HYDROCARBON GASES
GAS PURIFICATION SYSTEM
GASES
GAS SEPARATION
NH_3, H_2S, H_2O
LIQUIDS AND UNREACTED SOLIDS
CARBONACEOUS RESIDUES
PYROLYSIS
SOLIDS
SOLIDS SEPARATION
LIQUIDS
PRODUCT OIL
PRODUCT OIL

Figure 2. Synthoil system (3)

unit and the ammonia is used to produce ammonium sulfate. Sulfuric acid also may be produced (1).

Coal and residue from the reactor are used to produce a rich hydrogen (97.5 percent) mixture to use in the liquefaction reaction.

Major Operations and/or Modules--

- Sizing, drying and slurrying
- Hydrogenation
- Separation
- Hydrogen production

Material Inputs--

- Coal
- Catalyst - Co-Mo/SiO_2-Al_2O_3
- Hydrogen
- Monoethanolamine
- Water

Material Outputs--

- Synthoil
- Sulfur
- Ammonium sulfate
- Sulfuric acid
- Ash
- Carbonaceous residue
- Water from coal drying
- Dust from crushing
- Fuel gas
- Tar
- Spent catalyst
- Spent MEA
- Waste liquids, oil and water

- Blowdown and sludge from:
  - Power plant
  - Water treatment
  - Cooling tower

Advantages, Disadvantages, and Efficiency--

The high superficial velocity and rapid turbulent flow rates keep the catalyst surface free of deposits, inhibit agglomerating tendencies, and enhance hydrogen transfer (1). The short residence time and high yield would indicate possibilities for high production rates per unit volume in commercial-size operations.

On the other hand factors related to the maintenance of turbulent flow, good catalyst-reactant contact, and even flow distribution may limit practical diameter size in scale-up to commercial size. Other disadvantages are the relatively high pressure and the dependence on centrifugation for mineral separation. High yields of fuel oil, low sulfur (0.19 to 0.3 percent) and low-ash (one percent) ranged from 0.525 to 0.700 m^3 per metric ton of coal.

H-Coal System

Background--

The direct hydrogenation process developed by Berguis in Germany for conversion of coal to liquid products led to later development in the U.S. of the H-Coal process. It was developed by Hydrocarbon Research, Incorporated (HRI) as a further application of the H-Oil process ebullating bed technology originally employed to convert heavy oil residues into lighter fractions. The feed to hydrogen manufacture is liquid rather than solid. Direct catalytic processes use less hydrogen in converting coal to liquids than do the non-catalytic or indirect catalytic hydrogenation processes.

Early development work on the H-Coal process, beginning in 1964, involved research with a bench-scale unit and a process development unit, both located at HRI's Trenton Laboratory, under contract with the Department of Interior's Office of Coal Research. The government contract was cancelled in 1967 due to lack of funds but private industry continued to support the program. A conceptual process design was prepared and an independent evaluation in 1968 confirmed the technical and economic feasibility of the process (4).

In bench-scale and process development unit tests the process proved to be highly flexible. Bench-scale tests were conducted on many coals including eastern, midwestern and western bituminous coals, western subbituminous coals, lignite from Texas and North Dakota, and Australian brown coal. Variables investigated include: life and activity of catalyst type; temperature; pressure; coal feed rate; and slurry oil composition. The process development unit tests demonstrated sustained operational reliability (4).

Based on the data obtained from the bench-scale and process development units, design and engineering of a 544-metric ton per day pilot plant was initiated under the current DOE contract on December 1973. The final design of the pilot plant is complete and construction is underway at Catlettsburg, Kentucky. Ashland Synthetic Fuels, Inc., Ashland, Kentucky, and Hydrocarbon Research, Inc., Morristown, New Jersey are the prime contractors. Operation is scheduled for September 1, 1978 to June 1, 1980. The plant is to be dismantled and disposed by the end of 1980.

Ashland Synthetic Fuels will be responsible for construction and operation of the pilot plant. HRI will monitor the construction and operation of the plant to ensure that data suitable for a commercial plant design is obtained. A separate subcontractor will design the solids/ liquids separation system to be installed in the pilot plant. Product characteristics will be determined and operational problems identified (2).

System Description--

The H-Coal process utilizes an ebulliating bed reactor to continuously convert coal in a direct catalytic hydrogenation process.

The system configuration is depicted in the block flow diagram, Figure 3. Coal is crushed, dried, and slurried with recycled oil. Part of the coal is fed to the gasifier to provide for increased hydrogen production. Compressed hydrogen is added to the slurry; the mixture is preheated and charged continuously to the bottom of the reactor at a pressure of about 50.6 MPa. The cobalt/molybdenum catalyst is maintained in an expanded state by internal recycling of the reaction mixture. The temperature of the reactor, about 455°C, is controlled by adjusting the temperature of the reactants from the preheater (4).

Figure 3 depicts the disposition of by-products in the H-Coal system. Gas and vapor products leaving the top of the reactor are cooled to condense the heavier components. The gas cleanup system recovers light hydrocarbons, ammonia, and sulfur from the gas stream. The remaining hydrogen rich gas is recompressed and recycled to mix with the input slurry. The liquid from the condenser is fed to an atmospheric distillation unit. The liquid/solid product from the reactor is subjected to reduced pressure and the resultant vapors are passed to an atmospheric distillation unit that yields light and heavy distillate products. The bottoms product from the flash separator consists of solids and

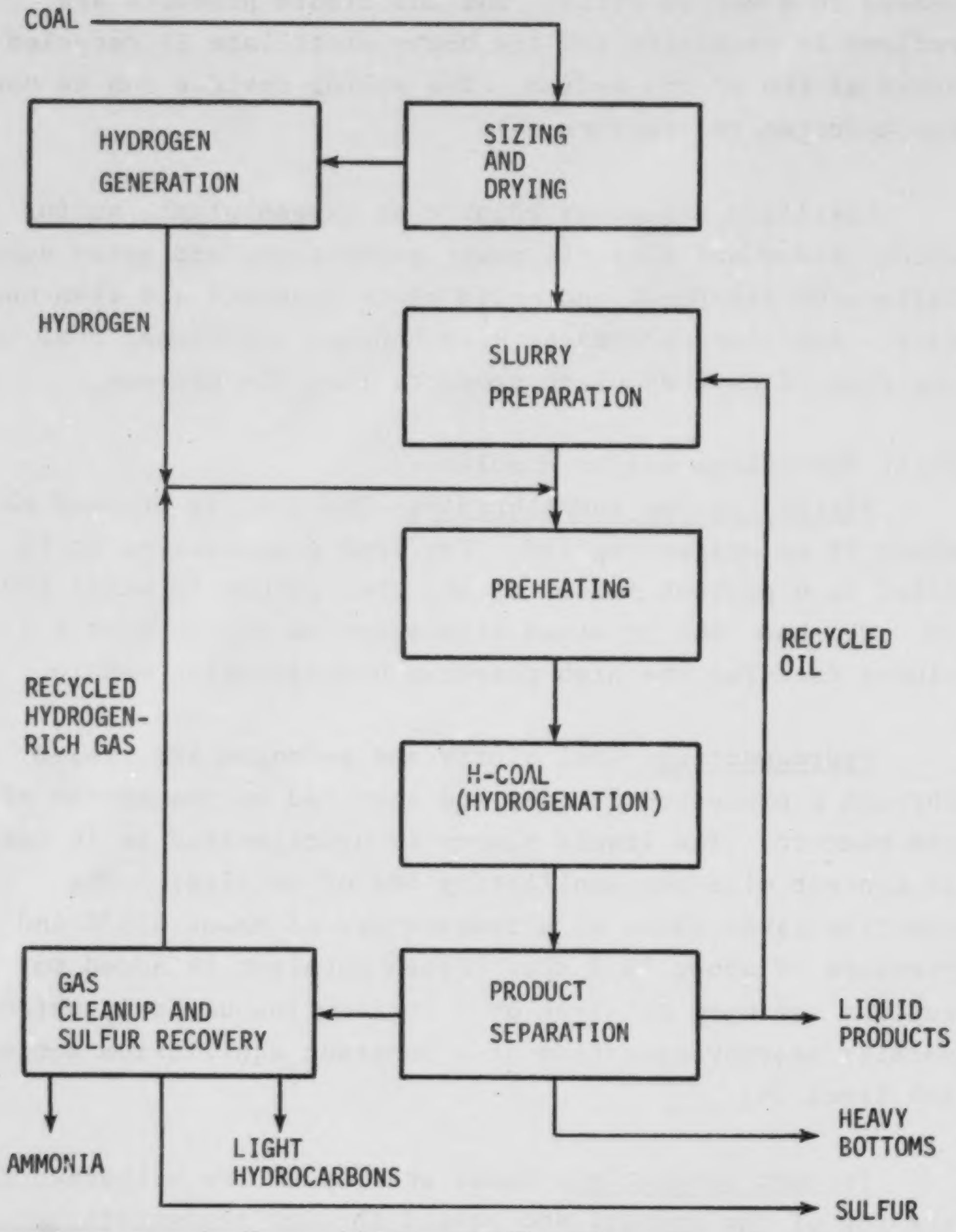

COAL
HYDROGEN GENERATION
SIZING AND DRYING
HYDROGEN
SLURRY PREPARATION
PREHEATING
RECYCLED OIL
RECYCLED HYDROGEN-RICH GAS
H-COAL (HYDROGENATION)
GAS CLEANUP AND SULFUR RECOVERY
PRODUCT SEPARATION
LIQUID PRODUCTS
HEAVY BOTTOMS
AMMONIA
LIGHT HYDROCARBONS
SULFUR

Figure 3. H-Coal system(4)

heavy oil. This mixture is passed through a hydroclone to remove the solids. Other separation methods have shown only limited effectiveness. The heavy oil is then further processed in a vacuum still. Gas and liquid products are refined as necessary and the heavy distillate is recycled to serve as the slurry medium. The solids residue can be used for hydrogen manufacture (4).

Auxiliary processes require an oxygen plant, sulfur plant, steam and electric power generation, and water supply. Wastewater treatment and solid waste disposal are also necessary. Auxiliary processes will consume additional fuel in the form of coal or clean products from the process.

Major Operations and/or Modules--

Sizing, drying and slurrying--The coal is crushed to about 18 mm and stockpiled. For feed preparation, it is dried to 4 percent moisture, and then ground to minus 250 µm. Crushed coal is mixed with recycled oil to form a slurry feed for the high pressure hydrogenation module.

Hydrogenation--Coal slurry and hydrogen are passed through a preheated furnace and then fed to the bottom of the reactor. The liquid slurry is hydrogenated as it comes in contact with the ebulliating bed of catalyst. The reaction takes place at a temperature of about 455°C and pressure of about 20.3 MPa. Fresh catalyst is added to replace the used catalyst on a semicontinuous basis which permits reactor operation at a constant equilibrium activity level (4).

Product separation--Gases and vapors are withdrawn from the top of the reactor and passed through condensers. Condensed oil vapors are sent to an atmospheric distillation unit. Further cooling of gases condenses a large amount of sour water containing ammonia, hydrogen sulfide, phenols, light oil, and suspended solids. Uncondensed gases are passed through an acid gas removal unit where hydrogen sulfide is removed and further processed to elemental sulfur. Part of the clean gas is used as plant fuel and part is recycled to the main reactor system. Fresh hydrogen is added to achieve the required concentration for use in the main reactor (4).

Solids separation--The heavier portion of the product oil leaves as a sidestream from the liquefaction reactor. It contains particulates such as mineral matter and unreacted coal which must be removed. The hot oil is flashed in a separator and the vapors are condensed and pumped to an atmospheric distillation unit.

Distillation--The bottoms product from the flash separator is further separated with a hydroclone, a liquid-solid separator, and a vacuum still. The overhead is a heavy oil refinery feedstock. The stream removed from the bottom of the vacuum tower contains heavy liquid residue together with some particulates. The bottoms product from the distillation unit is recycled for slurry preparation and the overhead stream of light liquid hydrocarbons is further refined as necessary. Synthesis gas for use in making hydrogen can be generated by using the slurry bottoms from the vacuum tower as feed to a slagging type gasifier. Supplemental coal feed may be needed (4).

Material Inputs--

- Coal
- Steam
- Air
- Catalyst
- Absorption solvent

Material Outputs--

- Synthetic oil
- Sulfur
- Ammonia
- Ash
- Residue
- Spent catalyst
- Spent solvent
- Water from coal drying
- Dust from coal crushing
- Fuel gas
- Tar
- Waste liquids, oil and water
- Blowdown and sludges from:
    - Power plant
    - Water treatment
    - Cooling tower

Advantages, Disadvantages, and Efficiency--

A consistent product quality is achieved because the operating temperature and the catalyst level can be controlled at constant values. The process can be operated to produce either a syncrude product or a residual fuel oil as the main product (4).

The reactor design uses a rotating shaft through the bottom of the vessel. At 20.3 MPa operating pressure, sealing of this shaft may present a difficult maintenance problem. Operation of hydroclones in the mineral separation step also may prove difficult. Factors related to an even distribution and good mixing may limit practical diameter size in scale-up of the reaction vessel to commercial size.

The system converts about 90 percent of the carbon contained in coal to a liquid. The pilot plant design capacity of 358 m^3/day from 544 metric tons of coal indicates an expected yield of 0.66 m^3/metric ton of coal.

Bergius System

Background--

The Bergius process is one of the forerunners in coal liquefaction technology. It was used by Germany to produce aviation fuel and diesel oil during World War II. There were 18 Bergius plants producing about 4.8 Mm^3 of oil per year. The process uses catalytic liquid phase hydrogenation to produce liquid fuels. Though there are no commercial Bergius plants operating currently, the process has led to the recent developments in the United States of the H-Coal and Synthoil processes (5).

System Description--

The major operations of the Bergius system are shown in Figure 4. Coal from the stockpiles is dried and finely ground. It is then mixed with process derived hydrocarbon liquid to form a paste containing approximately 40 percent coal. The paste is pressurized to about 68.6 MPa and heated to a temperature of 430°C. The heated paste and the recycled hydrogen-rich gas are then fed to a catalytic reaction zone.

The products from the first reaction are separated into an overhead gaseous stream, a light oil stream, and a heavy oil stream which contains unreacted coal and mineral matter. The overhead hydrogen-rich gas is scrubbed to remove any particulate matter and recycled to the reactor. The light oil stream is then catalyzed to produce materials similar to petroleum. The heavy oil stream is treated to separate untreated coal, catalyst, and mineral matter from the oil. Recovered oil is recycled to the past preparation area (6).

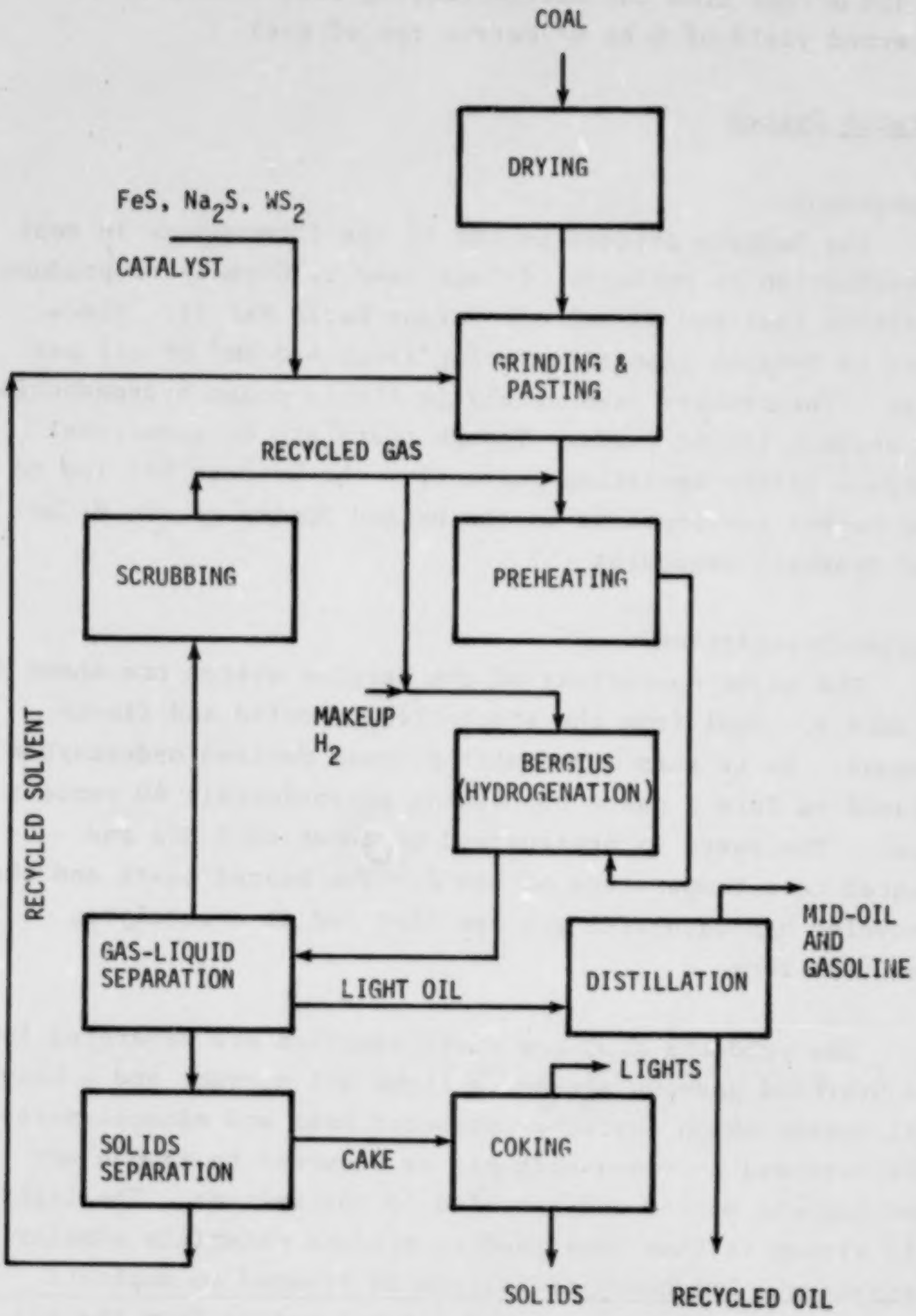

COAL
DRYING
FeS, Na$_2$S, WS$_2$
CATALYST
GRINDING & PASTING
RECYCLED GAS
SCRUBBING
PREHEATING
MAKEUP H$_2$
BERGIUS (HYDROGENATION)
RECYCLED SOLVENT
GAS-LIQUID SEPARATION
LIGHT OIL
DISTILLATION
MID-OIL AND GASOLINE
LIGHTS
SOLIDS SEPARATION
CAKE
COKING
SOLIDS
RECYCLED OIL

Figure 4. Bergius system (5)

Major Operations and/or Modules--

- Drying, sizing and pasting
- Hydrogenation
- Separation

Material Inputs--

- Coal
- Hydrogen
- Water
- Catalyst

Material Outputs--

- Carbonaceous residue
- Light oil
- Middle oil
- Wastewater
- Spent catalyst
- Sulfur
- Ammonia
- Dust
- Fuel gas
- Tar
- Waste oil
- Blowdown and sludges from:
  - Power generation
  - Water treatment
  - Cooling towers

Advantages, Disadvantages, and Efficiency--

A major advantage of the Bergius Process is that it has been operated commercially.

Two disadvantages are the high pressure requirements and high hydrogen consumption.

The catalysts were of poor quality by today's standards and this is reflected in the low yields of 30-55 percent.

Solvent Refined Coal System

Background--

Two alternatives are being pursued for electric power generation. One is to burn coal directly and remove particulates and SO_2 by scrubbing the stack gases; the other is to refine or clean the coal by removing sulfur and ash or mineral matter before it is fired in the utility steam generator, thus obviating the need for stack gas cleaning.

Solvent Refined Coal (SRC) represents the second alternative and is receiving serious consideration. The process was originally developed by Spencer Chemical Company for the United States Department of the Interior, Office of Coal Research. Gulf Oil subsequently acquired Spencer Chemical Company; development is continuing under the Pittsburgh and Midway Coal Mining Company, a part of Gulf Oil (2).

In 1972 an all-industry group, presently consisting of The Electric Power Research Institute and Southern Companies Services, initiated a pilot plant project to study the technological feasibility of the SRC Process. Early operations were performed at fixed conditions to establish process reliability. Later operations were conducted to study the effect of process variables such as temperature, pressure, retention time, solvent to coal ratio, and hydrogen consumption. Operating information from this pilot plant has been used to design and build a 45 metric ton per day pilot plant near Tacoma, Washington. This project, funded by DOE, is being developed by Pittsburgh and Midway Coal Mining Company (2).

Operation of and data from the Tacoma plant will provide opportunities for:

- Further study and development of the system
- Accumulation of engineering and cost data for evaluation of commercial possibilities, and design of demonstration or commercial plants
- Product evaluation and market development.

The Tacoma pilot plant has been in operation since October, 1974. It has recently produced about 2720 metric tons of SRC which was used for functional product testing in a 22 MW boiler.

The SRC process concept involves non-catalytic hydroliquefaction. Modifications of the SRC process include SRC II and the Gulf Catalytic Coal Liquid Process. A process development unit (PDU) using SRC technology is being operated by the University of North Dakota at Grand Forks, North Dakota, under DOE sponsorship. The unit is designed to process one-half metric ton of lignite per day.

System Description--

The SRC system converts high sulfur and high ash coal to a clean fuel product with a sulfur content of less than one percent and an ash content of 0.2 percent or less. SRC has a heating value of about 37.2 MJ/kg.

A block flow diagram of the SRC system is shown in Figure 5. In the coal preparation and handling area raw coal is unloaded, crushed, and stored in piles. The coal is sized, pulverized, and mixed with a recycled hydrocarbon solvent. The resulting coal/solvent slurry is mixed with a

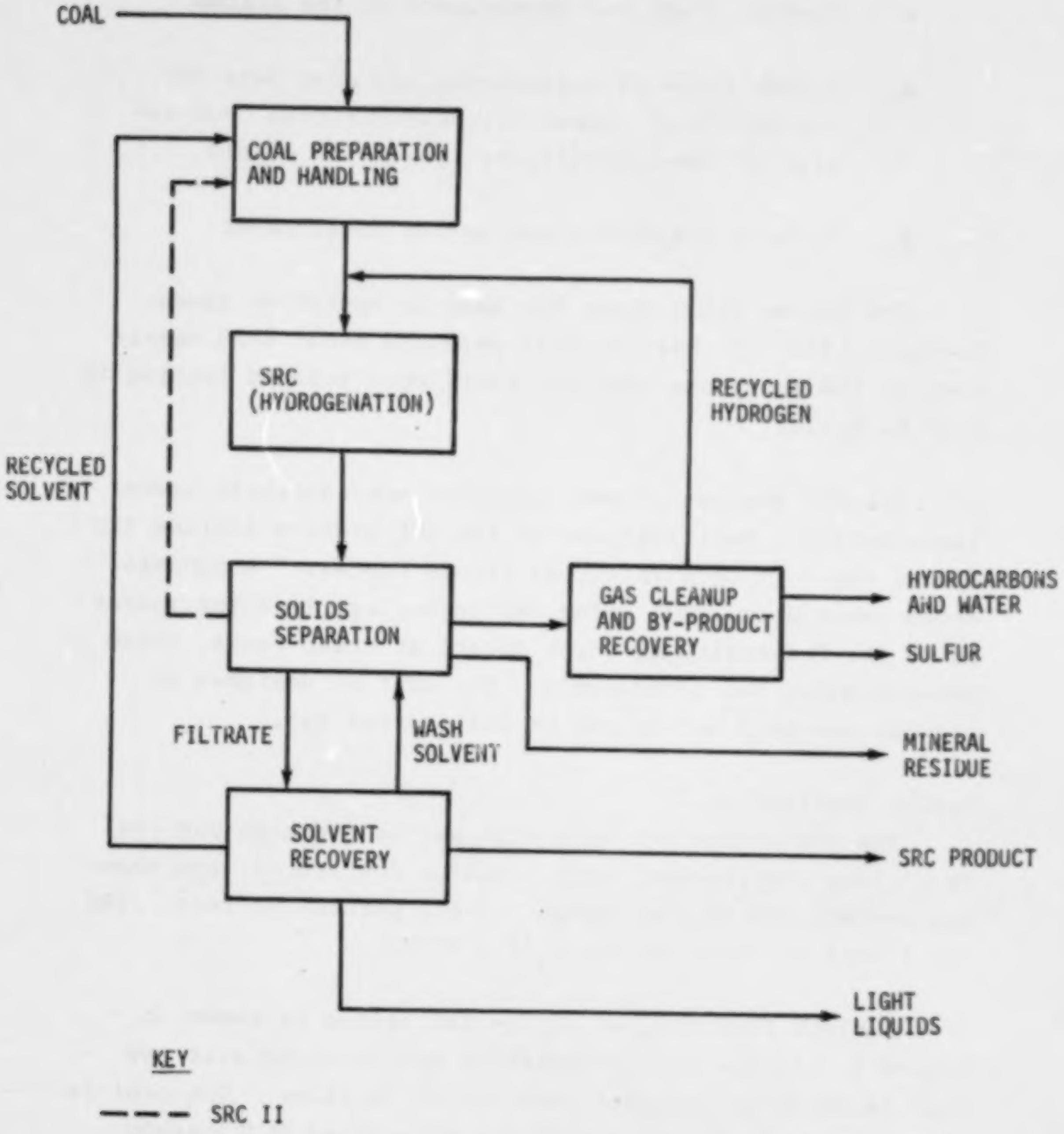

COAL
COAL PREPARATION AND HANDLING
SRC (HYDROGENATION)
RECYCLED HYDROGEN
RECYCLED SOLVENT
SOLIDS SEPARATION
GAS CLEANUP AND BY-PRODUCT RECOVERY
HYDROCARBONS AND WATER
SULFUR
FILTRATE
WASH SOLVENT
MINERAL RESIDUE
SOLVENT RECOVERY
SRC PRODUCT
LIGHT LIQUIDS
KEY
SRC II

Figure 5. Solvent refined coal system (7)

hydrogen-rich gas and then preheated. The preheated mixture enters the hydrogenation zone which operates at 425° to 480°C and 6.9 to 13.8 MPa, with about a 30 minute holding time. The coal is liquefied by reaction with hydrogen. The liquefied product contains some undissolved material, primarily mineral matter and undissolved coal. The excess hydrogen and gases produced in the reaction are separated from the slurry of undissolved solids and coal solution. The gaseous stream passes through a cleanup system to take out H_2S and CO_2 and is then recycled to the reaction zone. Fresh hydrogen from the hydrogen production area is added to this recycled gas stream. The slurry of solids and coal solution is cooled and the solids are separated from the coal solution, stored, and used for hydrogen generation. The coal solution is further separated into a light oil fraction a wash solvent fraction, the process solvent, and the solvent refined coal. The SRC is solidified by cooling. The gasification system will gasify either the residue or a mixture of residue and coal (5).

Auxiliary processes require steam electric power, cooling water, wastewater treatment utilities, and an oxygen plant for gasification.

Major Operations and/or Modules--

Sizing, drying, and slurrying--A flow diagram for this area is shown in Figure 6. As the coal is received it is separated according to lump size. Lumps smaller than 76 by 152 mm are sent to a primary crushing step which reduces their size to 19 mm. Large lumps are crushed to 76 by 152 mm and returned to the primary crushing step. The coal, from the primary crushing step is stored and later transferred to the pulverizer system. This system simultaneously grinds the coal to about 74 μm size and dries it to one to three percent moisture. The pulverized dry coal is slurried

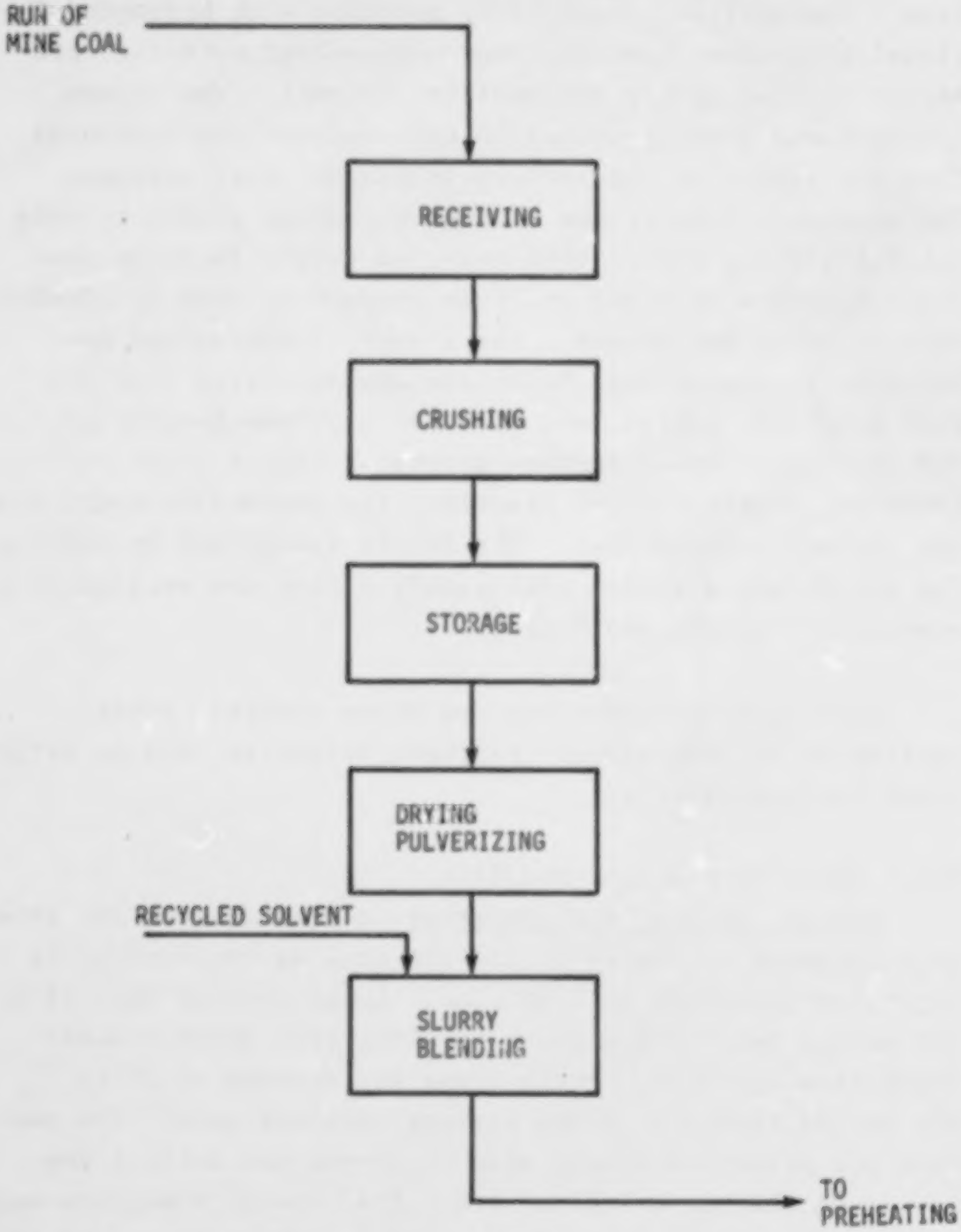

RUN OF MINE COAL
RECEIVING
CRUSHING
STORAGE
DRYING PULVERIZING
RECYCLED SOLVENT
SLURRY BLENDING
TO PREHEATING

Figure 6. Sizing, drying, pulverizing, and slurrying

with solvent. Fines from both primary crushing and pulverizing, less than 74 μm size, can be used to produce hydrogen for the hydrogenation step.

Hydrogenation--A flow diagram of the coal hydrogenation, mineral separation, and solvent recovery parts of the system are shown in Figure 7. A 70 to 85 percent hydrogen gas mixture is added to the coal/solvent slurry. These materials are first preheated and subjected to the conditions of the hydrogenation operation. Depending on the nature of the coal and its sulfur content, the temperature range is 425° to 495°C and the pressure range is 6.9 to 13.8 MPa. Other variables which affect this operation are the partial pressure of hydrogen, the residence time, and the solvent to coal ratio. These variables are interdependent, so a change in one may cause changes in the others. This gives flexibility to the process, permitting the output of a heavy or light product, the lighter product having the higher hydrogen content (5).

The hydrogenation or liquefaction operation produces a mixture of gases, vapors, liquids and solids. This mixture is cooled to 290°C and the vapor and gases are separated from the liquids and solids by a series of pressure reductions. The vapors consisting of light hydrocarbons, heavy hydrocarbons, and water are condensed and collected.

Solids separation--The mixture of coal solution and solids are separated by filtration or centrifugation. The solids contain mineral matter and undissolved coal. This residue is cooled to 38°C and stored. It can be gasified to produce the hydrogen required in the process.

Solvent recovery--Liquid material from the solid-liquid separation is heated to 425° to 470°C at about 0.71 MPa.

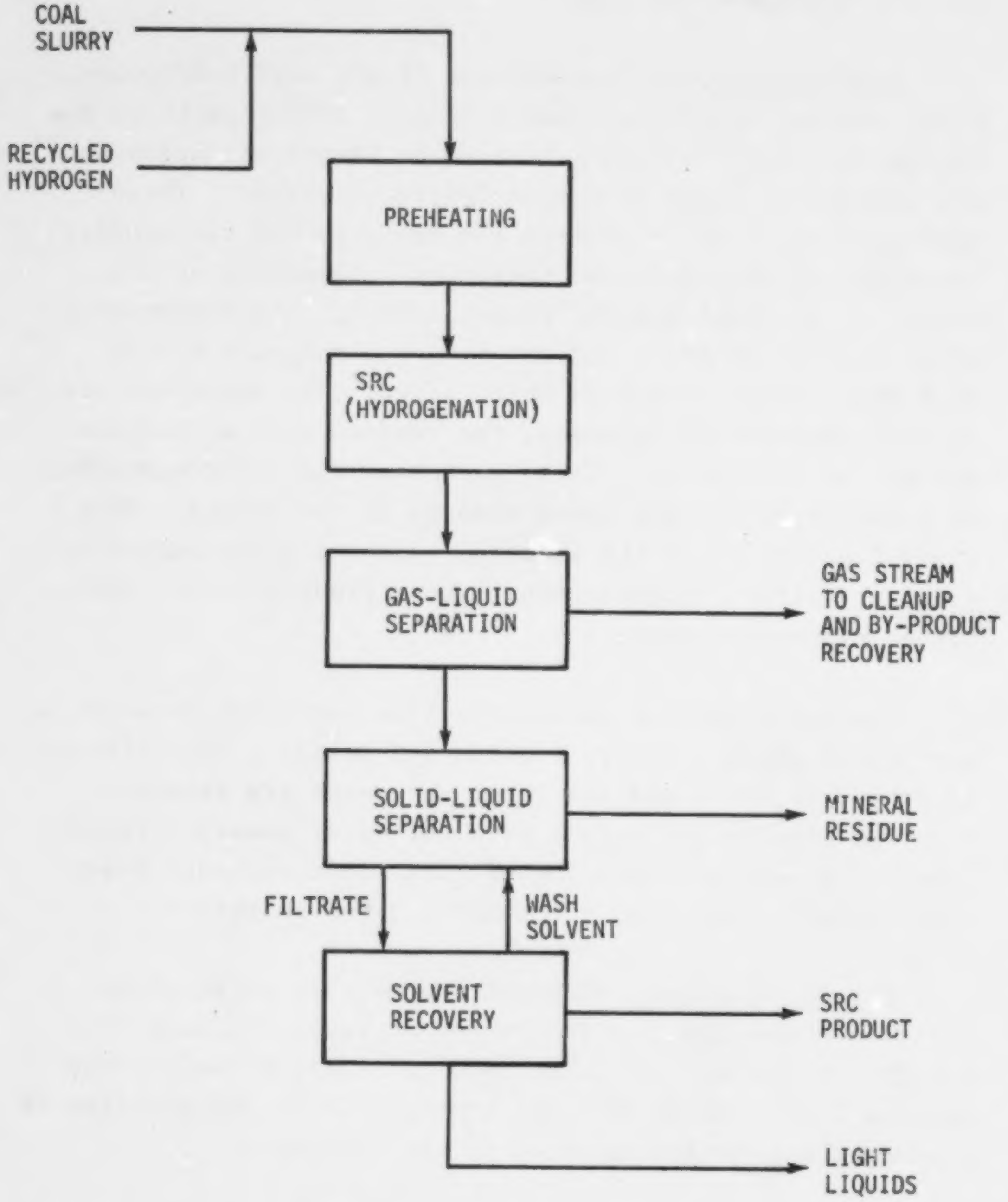

COAL SLURRY
RECYCLED HYDROGEN
PREHEATING
SRC (HYDROGENATION)
GAS-LIQUID SEPARATION
GAS STREAM TO CLEANUP AND BY-PRODUCT RECOVERY
SOLID-LIQUID SEPARATION
MINERAL RESIDUE
FILTRATE
WASH SOLVENT
SOLVENT RECOVERY
SRC PRODUCT
LIGHT LIQUIDS

Figure 7. Hydrogenation and mineral separation

All the unused process solvent and lighter liquids are vaporized. They are cooled, collected, and separated.

The remaining material is the molten solvent refined coal which is cooled from 316°C to about 66°C, the temperature at which it is solid.

Gas cleaning--The block flow diagram for gas cleaning is shown in Figure 8. In the hydrogenation operation most of the sulfur in the coal is converted to hydrogen sulfide and other gaseous compounds. Excess hydrogen is used in the operation and unused hydrogen can be recycled. However, it must first be cleaned to remove gaseous sulfur compounds. A number of patented processes are available for this purpose. Some remove carbon dioxide as well as hydrogen sulfide. After the hydrogen sulfide is removed from the gas stream, the solution used to absorb it is stripped to yield a concentrated hydrogen sulfide gas from which elemental sulfur is produced.

Material Inputs--

- Coal
- Steam, water
- Air
- Start-up solvent
- Absorption solvent

Material Outputs--

- Solvent refined coal
- Ash slag or ash
- Hydrocarbon gases
- Water (process, storm drainage from coal storage and preparation)
- Spent catalyst
- Sulfur

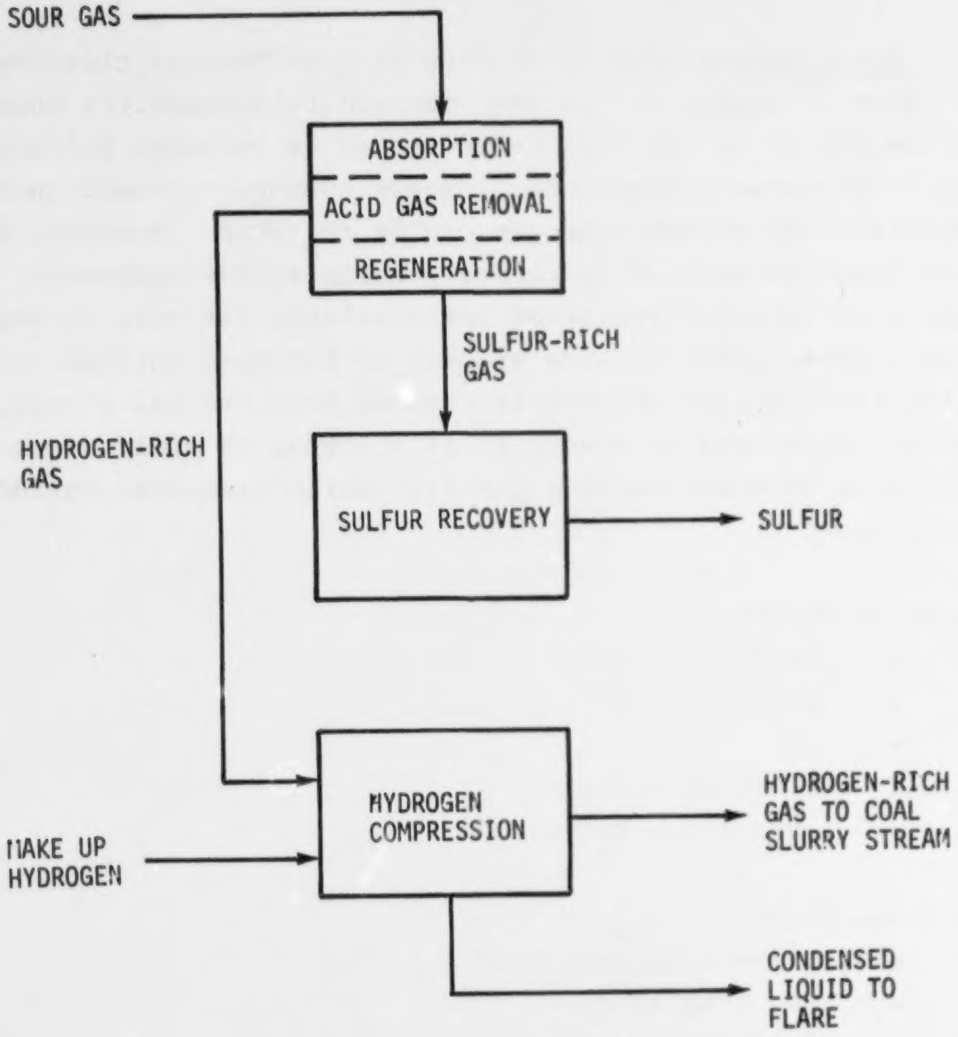

SOUR GAS
ABSORPTION
ACID GAS REMOVAL
REGENERATION
SULFUR-RICH GAS
HYDROGEN-RICH GAS
SULFUR RECOVERY
SULFUR
HYDROGEN COMPRESSION
MAKE UP HYDROGEN
HYDROGEN-RICH GAS TO COAL SLURRY STREAM
CONDENSED LIQUID TO FLARE

Figure 8. Gas cleaning

- Ammonia
- Coal dust
- Tar
- Waste liquids, oil and water
- Blowdown and sludges from:
  - Power plant
  - Water treatment
  - Cooling towers

Advantages, Disadvantages and Efficiency--

The process requires no catalyst and lower amounts of hydrogen than most alternative processes. The solid product is low in sulfur and ash and has a high heating value. A range of products, solids, heavy liquids and light liquids is permitted by the flexibility of the SRC process. Recent improvements in the original process provide for product slurry recycling which causes a self-catalytic effect that improves hydrogenation. The improved SRC-II process also avoids the troublesome filtration step in the mineral separation area. Yields of about 60 percent for the solid and 42 percent for the liquid product have been achieved. The major difficulties lie in operating costs for filtration and development of handling methods of the solid product.

CO-Steam System

Background--

In 1921 two German scientists, F. Fischer and H. Schrader, reported the use of carbon monoxide as a reducing agent in the solubilizing of coal. Interest in this discovery was lacking at that time because of low yields of heavy products and a greater interest in motor fuels. Since the late 1960s the work has been extended, modified, and improved. The process now has good commercial potential. This later work indicated the importance of using a solvent with a coal which has not been subjected to aging, drying, or oxidation. Carbon monoxide, water, and coal at 380° to 400°C yielded a benzene-soluble solid or semi-solid product. More recent work has been conducted to substitute synthesis gas for carbon monoxide and to make a product with sufficient fluidity for use as a coal slurry vehicle (8).

The U.S. Department of the Interior, Bureau of Mines has developed a new process, CO-Steam, that does not use hydrogen directly. In this process coal reacts with carbon monoxide and steam instead of hydrogen. It does not require a catalyst to convert low rank coals, such as lignite, into a low sulfur liquid fuel. There is usually enough water in lignite to supply the needs of the process. The water or steam supplies active hydrogen by reaction with the carbon monoxide. Alkaline carbonates are naturally occurring catalytic agents in lignite (8).

System Description--

Figure 9 is a schematic of the major CO-Steam steps. Lignite is pulverized and mixed with some of the product oil. This slurry is fed to the reactor which operates at a temperature of 380° to 400°C and a pressure of 20.5 to 27.4 MPa. Synthesis gas or carbon monoxide is fed to the reactor at high pressure. Reaction time is about one hour. Synthesis gas or carbon monoxide reacts with water contained in the lignite to produce hydrogen which then reacts with lignite to form a liquefied coal product.

Product gas is separated from the product liquid stream in a pressure reduction step. The liquid fuel product stream contains unreacted solids and ash which are removed by centrifugation. The unreacted solids residue can be utilized to produce the synthesis gas required by the

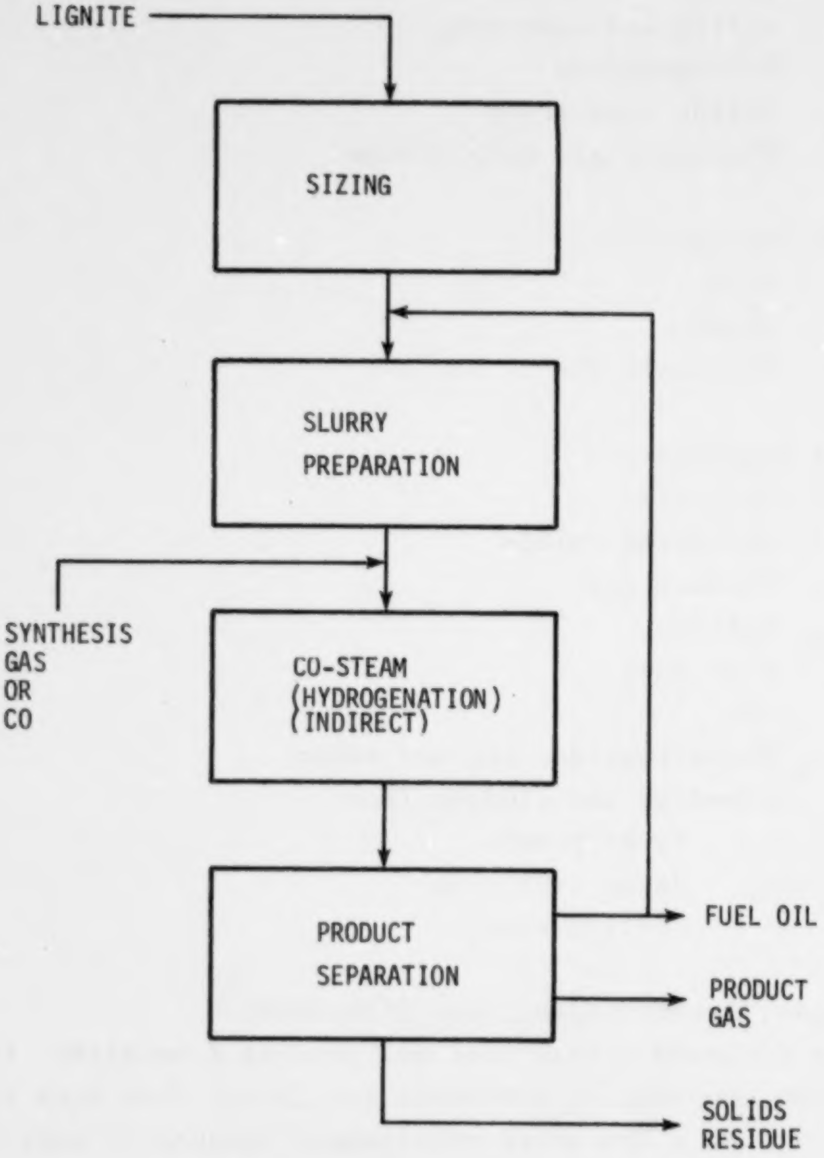

LIGNITE
SIZING
SLURRY PREPARATION
SYNTHESIS GAS OR CO
CO-STEAM (HYDROGENATION) (INDIRECT)
PRODUCT SEPARATION
FUEL OIL
PRODUCT GAS
SOLIDS RESIDUE

Figure 9. CO-Steam system (5)

process. The product fuel oil can also be further hydrogenated to obtain gasoline.

Major Operations and/or Modules--

- Sizing and slurrying
- Hydrogenation
- Solids separation
- Synthesis gas manufacture

Material Inputs--

- Coal
- Water
- Synthesis gas

Material Outputs--

- Fuel oil
- Unreacted solids
- Product gas
- Residue
- Coal dust
- Tar
- Waste liquids, oil and water
- Blowdown and sludges from:
    - Power plant
    - Water treatment
    - Cooling tower

Advantages, Disadvantages, and Efficiency--

The CO-Steam system does not require a catalyst, it can use carbon monoxide or synthesis gas rather than pure hydrogen and it has a low water requirement because it uses the water occurring naturally in the lignite feed.

However, it does employ centrifugation, a troublesome operation, for mineral separation and it may be limited to lignite as a feed material.

The process converts about 70 percent of the carbon to benzene-soluble fuel.

Donor Solvent System

Background--

The conversion of coal to liquid fuels by the high-pressure Bergius process was used in Germany for 15 years or more. It operates in the pressure range of 22.5 to 62.0 Mpa. Disadvantages of high pressure processes are the expense of high pressure vessels and of hydrogen compression. Processes operating below 9.8 MPa, however, generally use either direct catalysis (in the reactor) or indirect catalysis, via a recycled solvent. Exxon is developing an indirect catalyst method. In the Exxon Donor Solvent (EDS) system, Figure 10, the donor solvent is prepared in a separate, fixed bed, catalytic hydrogenation step (9). Other very similar systems are the Consol Synthetic Fuel System, Figure 11, Arthur D. Little System, Figure 12, Liqui-Coal System, Figure 13, and Pott-Broche System, Figure 14.

Research was begun in 1966 to identify the basic EDS process. It included studies on both hydrogenated and unhydrogenated recycled solvents. Conditions ranged from 400° to 425°C at pressures of 2 to 2.5 MPa, to 425° to 480°C at 9.8 to 19.6 MPa. A number of different solid-liquid separation methods were studied. Equipment was tested in an integrated pilot plant system with a capacity of one-half ton per day. Techniques were developed for analyzing product and intermediate streams. Based on these studies, the separation operation chosen was vacuum distillation and a

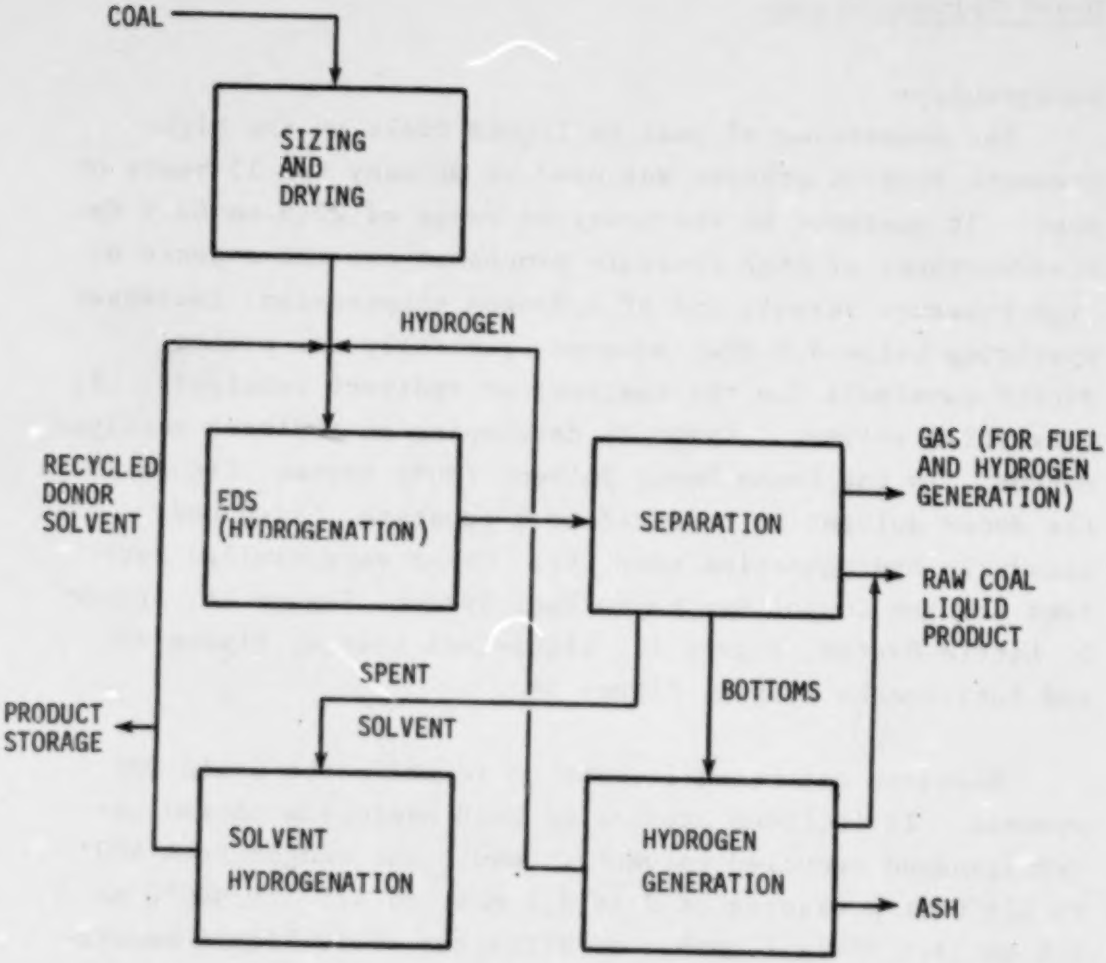

COAL
SIZING AND DRYING
HYDROGEN
RECYCLED DONOR SOLVENT
EDS (HYDROGENATION)
SEPARATION
GAS (FOR FUEL AND HYDROGEN GENERATION)
RAW COAL LIQUID PRODUCT
SPENT SOLVENT
BOTTOMS
PRODUCT STORAGE
SOLVENT HYDROGENATION
HYDROGEN GENERATION
ASH

Figure 10. Exxon Donor Solvent (EDS) system (9)

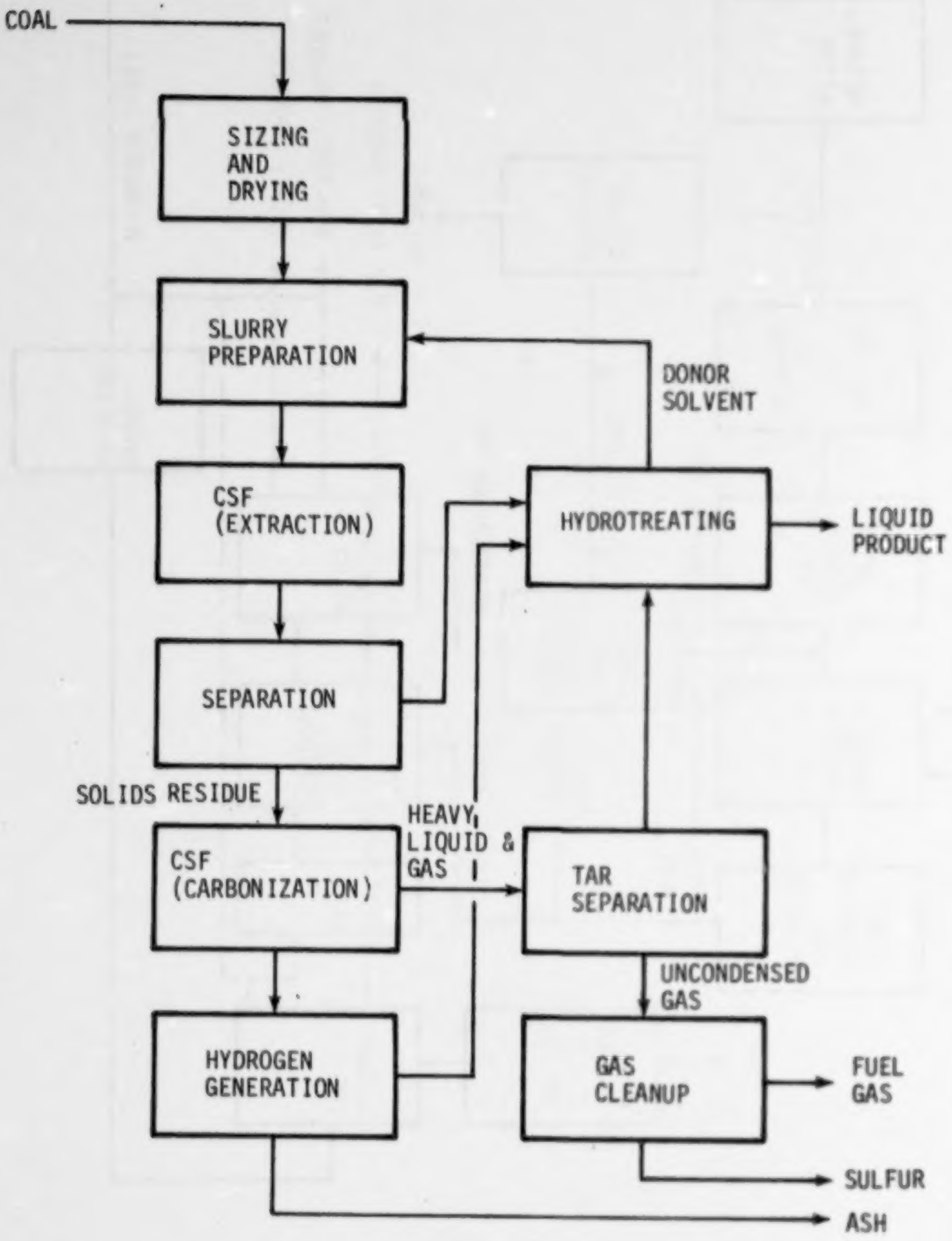

COAL
SIZING AND DRYING
SLURRY PREPARATION
DONOR SOLVENT
CSF (EXTRACTION)
HYDROTREATING
LIQUID PRODUCT
SEPARATION
SOLIDS RESIDUE
HEAVY LIQUID & GAS
CSF (CARBONIZATION)
TAR SEPARATION
UNCONDENSED GAS
HYDROGEN GENERATION
GAS CLEANUP
FUEL GAS
SULFUR
ASH

Figure 11. Consol Synthetic Fuel (CSF) system (10)

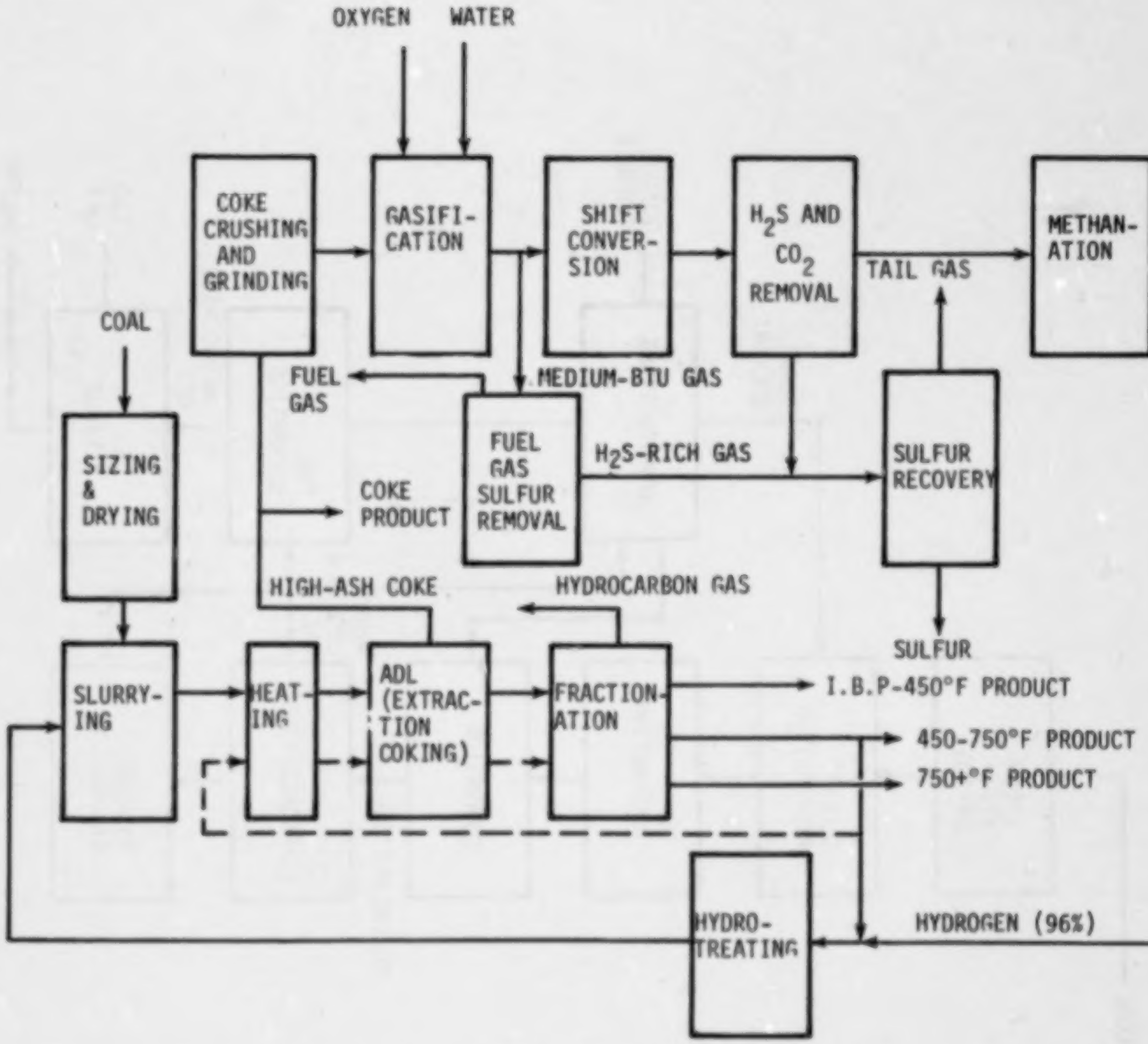

OXYGEN
WATER
COKE CRUSHING AND GRINDING
GASIFICATION
SHIFT CONVERSION
H_2S AND CO_2 REMOVAL
METHANATION
TAIL GAS
COAL
FUEL GAS
MEDIUM-BTU GAS
SIZING & DRYING
FUEL GAS SULFUR REMOVAL
H_2S-RICH GAS
SULFUR RECOVERY
COKE PRODUCT
HIGH-ASH COKE
HYDROCARBON GAS
SULFUR
SLURRYING
HEATING
ADL (EXTRACTION COKING)
FRACTIONATION
I.B.P-450°F PRODUCT
450-750°F PRODUCT
750+°F PRODUCT
HYDROTREATING
HYDROGEN (96%)

Figure 12. Arthur D. Little (ADL) system (11)

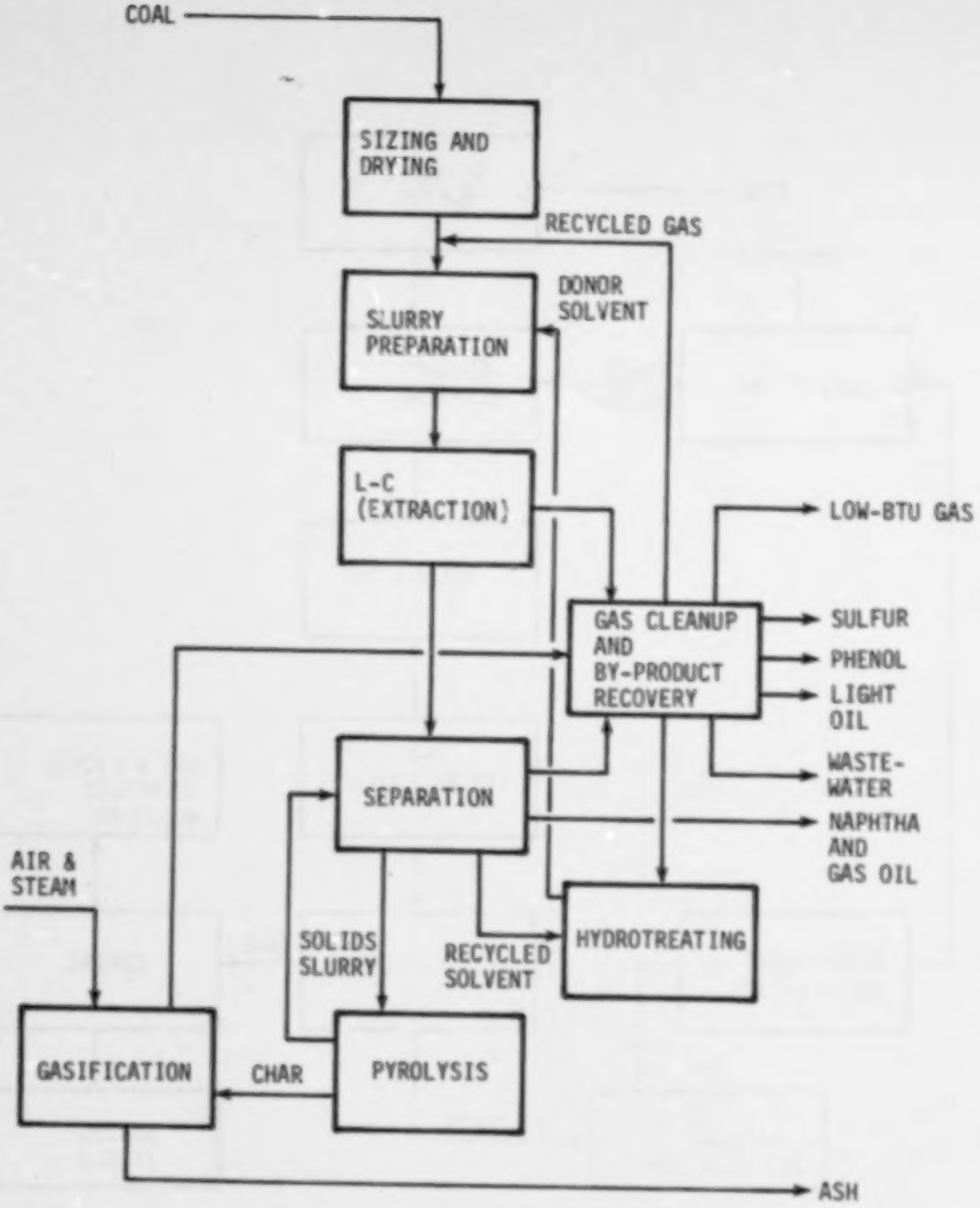

COAL
SIZING AND DRYING
RECYCLED GAS
SLURRY PREPARATION
DONOR SOLVENT
L-C (EXTRACTION)
LOW-BTU GAS
GAS CLEANUP AND BY-PRODUCT RECOVERY
SULFUR
PHENOL
LIGHT OIL
SEPARATION
WASTE-WATER
NAPHTHA AND GAS OIL
AIR & STEAM
SOLIDS SLURRY
RECYCLED SOLVENT
HYDROTREATING
GASIFICATION
CHAR
PYROLYSIS
ASH

Figure 13. Liqui-Coal (L-C) system (12)

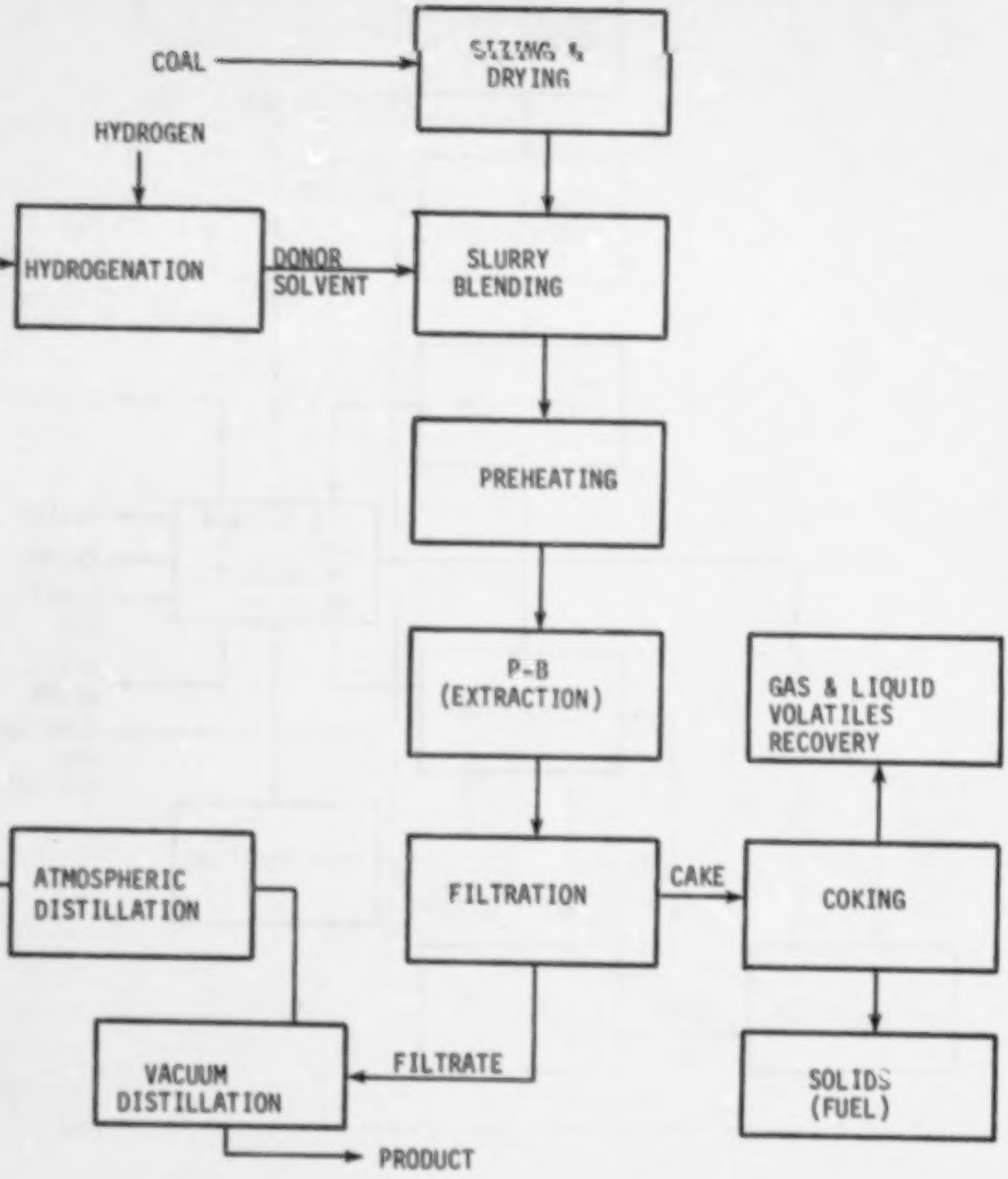

COAL
SIZING &
DRYING
HYDROGEN
HYDROGENATION
DONOR
SOLVENT
SLURRY
BLENDING
PREHEATING
P-B
(EXTRACTION)
GAS & LIQUID
VOLATILES
RECOVERY
ATMOSPHERIC
DISTILLATION
FILTRATION
CAKE
COKING
VACUUM
DISTILLATION
FILTRATE
SOLIDS
(FUEL)
PRODUCT

Figure 14. Pott-Broche (P-B) system (5)

hydrogenated recycled solvent operation was selected for further development.

Studies of system variables are continuing in a 0.9-metric ton per day pilot plant. Plans for a 225-metric ton per day pilot plant were announced in July, 1977. This work is sponsored by DOE.

System Description--

The four major areas of the EDS system are shown in the preceding simplified block diagram in Figure 10. Prepared coal feed, hydrogen, and recycled solvent are inputs to the liquefaction area. These materials react to produce raw coal liquid, gases, and a heavy bottoms stream containing unreacted coal and mineral matter. The recycled solvent is separated from this mixture in the separation area. The solvent goes to the solvent hydrogenation area where it is regenerated catalytically. Heavy bottoms from the separation area are used to produce additional hydrogen or fuel gas in the hydrogen manufacturing area. Gas generated in the liquefaction area is used as fuel or for hydrogen manufacture. The raw coal liquids may be further hydrotreated, depending on the end use. The donor solvent is prepared from the middle fraction of the coal liquefaction product, which is treated by selective catalytic hydrogenation. The main function of the solvent is to provide hydrogen to free radicals formed by thermal "cracking" of coal "molecules." The solvent also carries the coal into the reactor, helps to dissolve the coal particles, and improves operability as compared to unhydrogenated solvent. Addition of hydrogen to the liquefaction step was found to reduce solvent requirements (9).

Major Operations and/or Modules--

Sizing and drying--Coal, bituminous or subbituminous, is dried, ground, and screened to minus 595 μm. Prepared feed coal is supplied to the slurry preparation system. The coal/solvent slurry is metered continuously to the hydrogenation systems.

Hydrogenation--The slurry feed stream is preheated before it enters the reaction zone. Hydrogen gas is also preheated, and fed to the reaction zone, either separately or mixed with the slurry feed. Conditions for the liquefaction process are: pressure 9.8 to 17.1 MPa; temperature 370° to 380°C; solvent-to-coal ratio of 1.2 to 2.6; and residence time of 15 to 140 minutes (9).

Separation--The material from the liquefaction process consists of gas, raw coal liquids, and a heavy stream containing unreacted coal and mineral matter. The pressure on this material is decreased in several steps. Some gas and water vapor are removed in the first step. This gas is sent to the recycled gas cleanup system for recovery of hydrogen and reuse in liquefaction (9).

In the second depressurizing step more gas is released, containing heavier hydrocarbons, suitable for fuel gas. In the third step the remaining liquids and solids are heated and flashed under vacuum. This releases additional gas and vaporizes light oil containing some gas. The bottoms material contains the solids residue, i.e., unreacted coal, mineral matter, and heavy tars.

Solvent hydrotreating--The light vacuum gas oil, combined with other liquid hydrocarbon streams, is catalytically hydrotreated. Gaseous and liquid products from this reaction are separated. The liquid is a mixture of liquefied coal product, a heavier fraction with a higher boiling point, and a lighter fraction with a lower boiling point. The solvent fractionation system separates the desired liquefied coal product from the higher and lower boiling fractions of the hydrotreated liquid product. Some of this mid-range solvent is recycled to the slurry preparation area and the rest is sent to product storage (9).

Hydrogen manufacture--The gas streams from the first depressurizing step and the hydrotreating area are scrubbed with monoethanolamine to remove hydrogen sulfide and carbon dioxide. If the hydrogen content is not high enough, high purity makeup hydrogen is added. This stream is then compressed and sent to the hydrogenation and solvent hydrotreating areas (9).

High purity hydrogen can be made from fuel gas and solids residue from the separation section.

Material Inputs--

- Coal
- Cobalt-molybdate, catalysts
- Monoethanolamine
- Water

Material Outputs--

- Low sulfur fuel oil
- Naphtha
- Fuel gas
- Sulfur
- Residue
- Ammonia
- Coal dust
- Tar
- Spent catalyst

- Spent MEA
- Waste liquids, oil and water
- Blowdown and sludges from:
  - Power plant
  - Water treatment
  - Cooling tower

Advantages, Disadvantages, and Efficiency--

The system uses steps that entail engineering and design technology derived from the petroleum industry. It operates at relatively low pressure 10.2 to 17.1 MPa. It has flexibility; varying amounts of hydrogen can be added to the slurry ahead of the preheater which decreases solvent hydrogenation requirements while improving yields and physical properties of the products. It does not require mechanical separation devices or catalysts that are sensitive to solids (9).

Key areas requiring scaled-up demonstration are the 3-phase coal liquefaction reactor and the coal slurry preheat furnace. The overall process efficiency is 65 to 75 percent and the maximum practical liquid yield is 0.47 to 0.54 m^3/metric ton.

PYROLYSIS AND HYDROCARBONIZATION

Char-Oil-Energy Development (COED) System

Background--

The COED system converts coal to low sulfur synthetic crude oil, clean fuel gas, and char. The oil product can be used directly as fuel oil or as a feedstock for oil refining. Fuel gas is generally defined as a combustible gas having an intermediate or low heating value of 5.6 to 22.4

MJ/m^3. The gas can be further purified and methanated to produce pipeline quality gas, which is the equivalent of natural gas, having a heating value of 33.5 MJ/m^3.

Pyrolysis processes, which are essentially coking operations, produce significant quantities of char which must be disposed of economically. The char has good fuel properties and for certain applications is better than the coal from which it was made. For example, char produced from two highly volatile, bituminous coals had heating values equal to 90 percent of that of the coal, sulfur content was reduced by 17 percent, hydrogen by 81 percent, and volatile matter by 90 percent, but ash increased by 191 percent. The syncrude oil or liquid product contains small amounts of oxygen, nitrogen, and sulfur which can be removed by hydrotreatment. Subbituminous coals with a significant content of volatile components produce more oil than other coals (13).

Project COED was initiated in 1962 when the FMC Corporation, under sponsorship of the Office of Coal Research, Department of the Interior started research work to upgrade coal to more valuable products. Following bench-scale studies, operation of a 45-kg per hour PDU was undertaken during 1965 to 1967. Western and midwestern coals were processed in a multi-stage, fluidized bed, pyrolysis system (2).

A small bench scale hydrotreating study was performed by Atlantic Richfield Company and economic evaluations for a conceptual commercial design were made. Promising results from these preliminary studies led to the design, construction, and operation of a 33-metric ton per day pilot plant at the FMC Corporation's Research and Development Center in Princeton, New Jersey. The plant was completed in August, 1970, and the first successful 30-day run was made in December, 1970. The pilot plant completed a number of long-term runs with good operating reliability. The plant processed about 18,144 metric tons of a wide variety of American coals including the highly caking types. Sufficient engineering data was obtained for the design of a commercial plant. All project objectives were completed and the pilot plant was shut down in April, 1975. It has since been dismantled.

The Seacoke process is a similar process, using a five-stage, fluidized bed, pyrolysis system. The Seacoke products are syncrude, char, and fuel gas. The Seacoke process operates at atmospheric pressure and in the temperature range of 315° to 870°C.

System Description--

A general block flow diagram is shown in Figure 15. The prepared coal is fed to the first stage fluid bed. Recycled gas is used as the fluidizing medium. Vapors from Stage 1 are sent to a gas scrubber and the char passes on to the second fluid bed stage. The temperature of Stage II is maintained by hot gas from Stage III. Vapors from Stage II are sent to product recovery for separation of fuel gas and the product tar oil. The fuel gas is further processed through a gas cleaning system to recover elemental sulfur. The clean gas can be used to hydrotreat the product oil. The char from Stage II goes to the third stage.

Fluidizing gas for Stage III is the gas from Stage IV. Char from Stage III is fed to Stage IV where it reacts with oxygen and steam. Pressures in the pyrolysis operation range between 145 and 172 kPa. The temperature in each stage must be held just below the temperature at which the coal

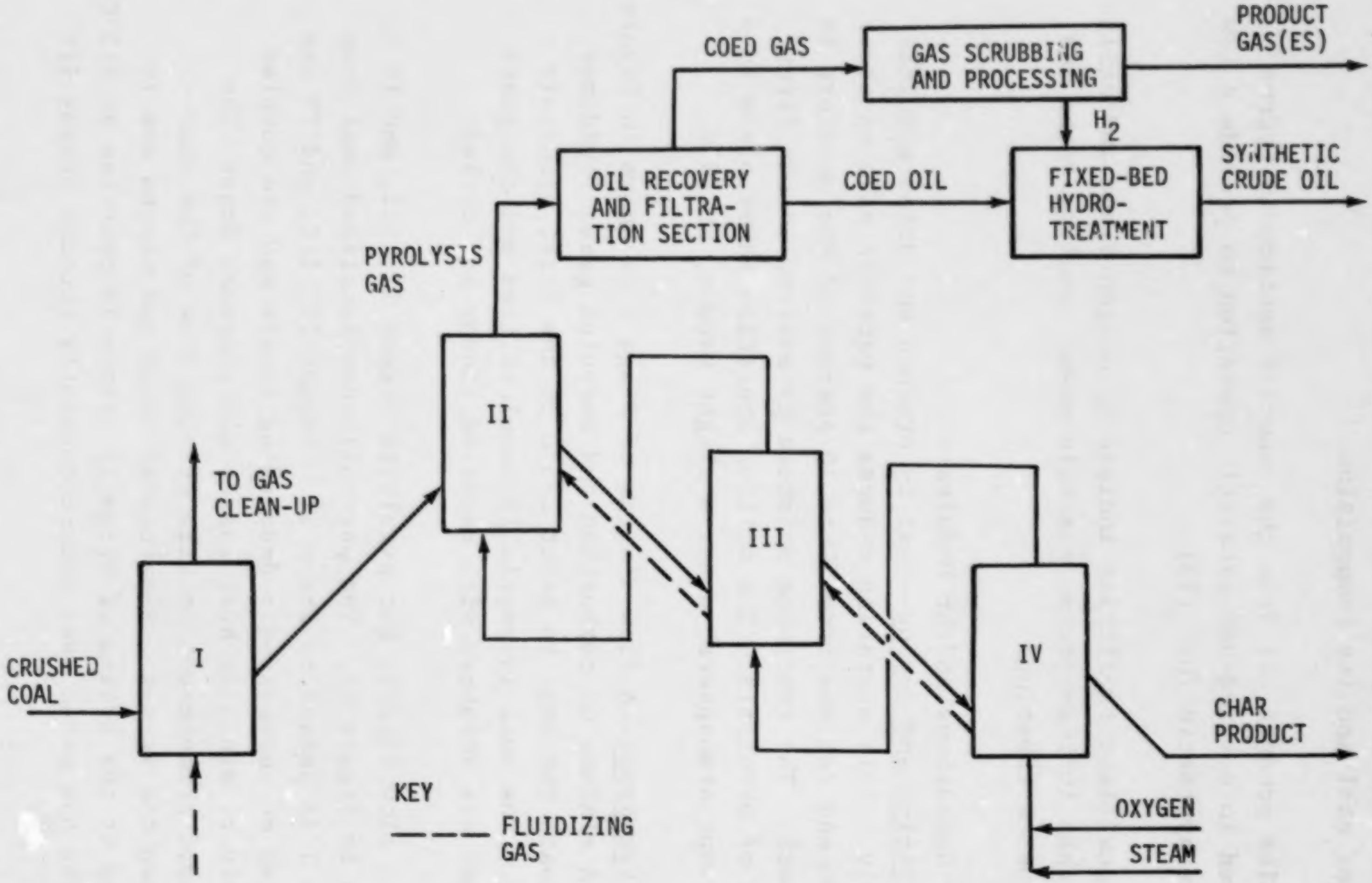

PRODUCT GAS(ES)
COED GAS
GAS SCRUBBING AND PROCESSING
H_2
OIL RECOVERY AND FILTRATION SECTION
COED OIL
FIXED-BED HYDRO-TREATMENT
SYNTHETIC CRUDE OIL
PYROLYSIS GAS
TO GAS CLEAN-UP
II
III
I
IV
CRUSHED COAL
CHAR PRODUCT
KEY
FLUIDIZING GAS
OXYGEN
STEAM

Figure 15. COED system (2)

agglomerates and plugs the bed. This value depends on the type of coal and its composition.

The product oil from the recovery section is hydrotreated in a fixed-bed catalytic operation to provide a low sulfur synthetic fuel (13).

Auxiliary facilities include an oxygen plant and utilities that include steam, electric power, cooling water and wastewater treating.

Major Operations and/or Modules--

Sizing and drying--Coal is crushed and dried simultaneously. This operation reduces the particle size to about 1.6 mm and removes from 60 to 70 percent of the moisture in the coal. The remaining moisture is evolved in the first stage of pyrolysis. The milling operation takes place in a gas swept atmosphere, under a slight vacuum, at 70°C.

Pyrolysis--A flow diagram of Stage I is shown in Figure 16. A mixture of combustion and recycled gases fluidizes and heats the coal to about 175°C in the first pyrolysis stage. The coal is partially devolatilized and the gases evolved are scrubbed with recycled liquor and cooled.

A flow diagram for pyrolysis stages II, III, and IV is shown in Figure 17. The partially devolatilized coal from Stage I is passed to Stage II. Stages II, III, and IV are located on successively descending levels and are coupled closely to minimize heat losses and pressure drops. The cascaded arrangement permits gravity flow of the char between the stages. Superheated steam and oxygen are injected at the bottom of Stage IV. Stage IV operates at 815°C and the hot gases pass countercurrently through Stages III

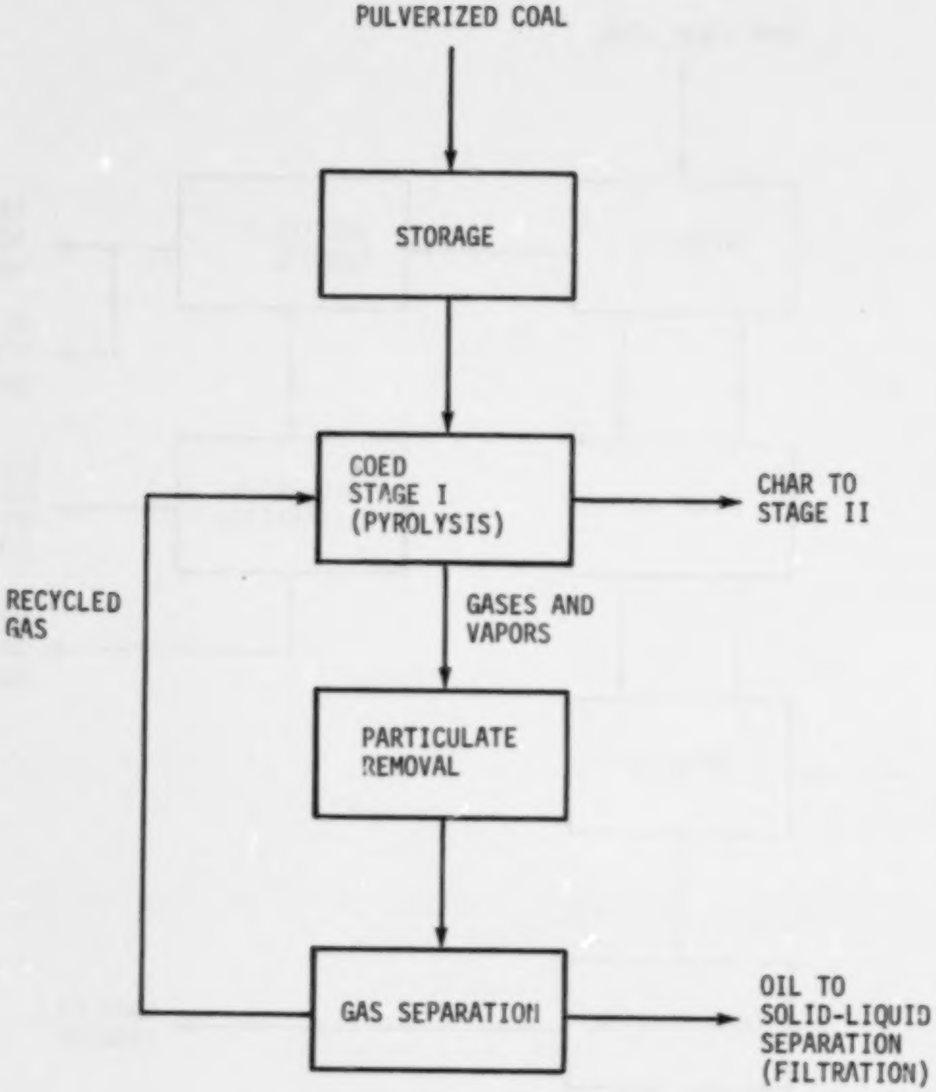

PULVERIZED COAL
STORAGE
COED
STAGE I
(PYROLYSIS)
CHAR TO
STAGE II
RECYCLED
GAS
GASES AND
VAPORS
PARTICULATE
REMOVAL
GAS SEPARATION
OIL TO
SOLID-LIQUID
SEPARATION
(FILTRATION)

Figure 16. Stage I, COED system (13)

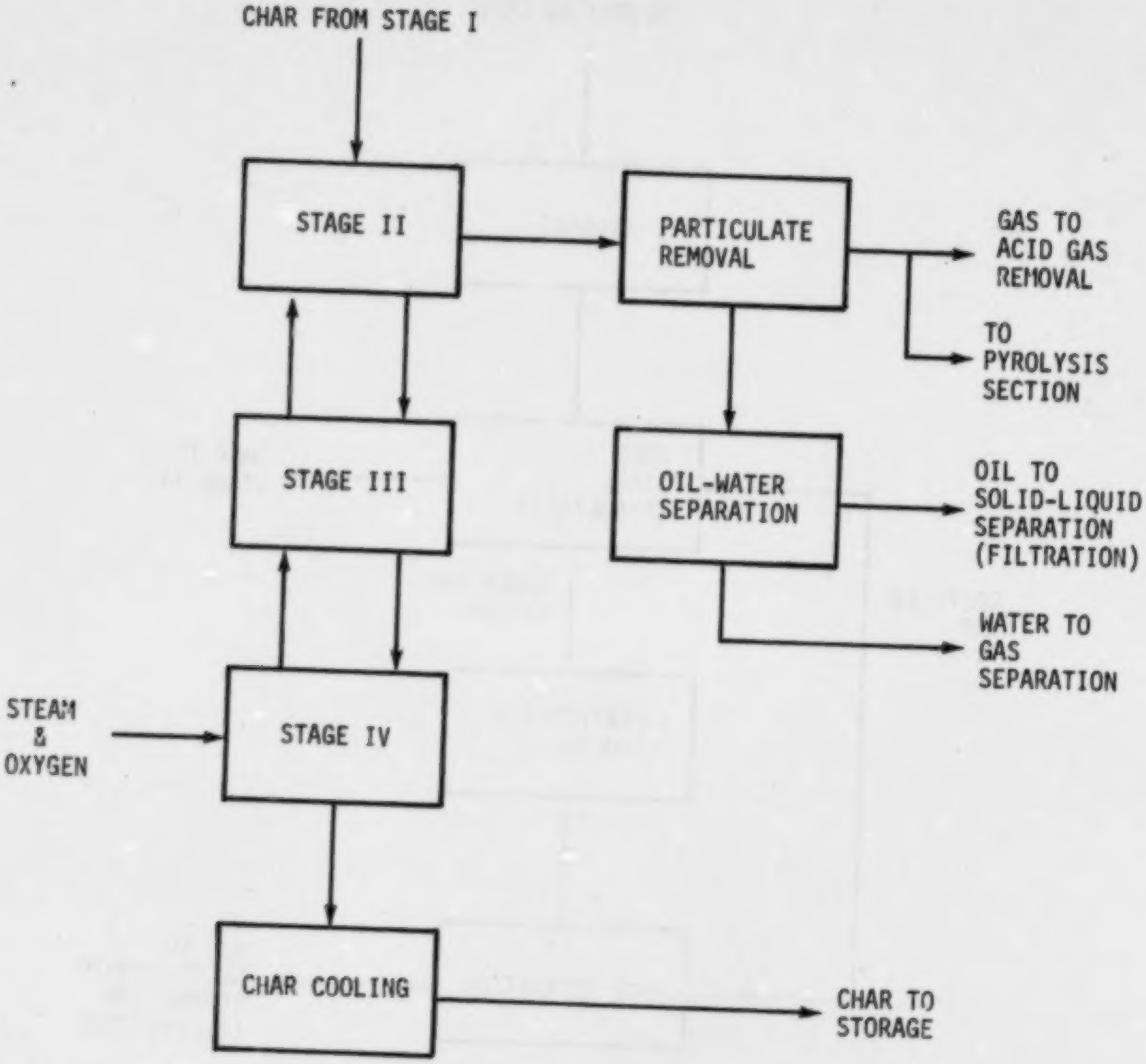

CHAR FROM STAGE I
STAGE II
PARTICULATE REMOVAL
GAS TO ACID GAS REMOVAL
TO PYROLYSIS SECTION
STAGE III
OIL-WATER SEPARATION
OIL TO SOLID-LIQUID SEPARATION (FILTRATION)
WATER TO GAS SEPARATION
STEAM & OXYGEN
STAGE IV
CHAR COOLING
CHAR TO STORAGE

Figure 17. Stages II, III and IV, COED system (13)

and II, providing the fluidizing medium. Stages II and III operate at about 430°C and 540°C respectively.

All stages are equipped with internal particulate separations systems to remove entrained solids from the exit gases. Most of the volatile matter contained in the coal is evolved in the second stage. The rest of the volatile matter evolves in the third and fourth stages. The pyrolysis gases and oil vapors from the second stage pass through an external particulate separation system to remove solids which would otherwise collect in and plug subsequent processing steps. They are next treated in an absorption system which removes the oil vapors, treated for removal of hydrogen sulfide and carbon dioxide, and then used as product gas.

Oil and water condensed from the pyrolysis gas/vapor stream are separated into two oil fractions, one heavier and one lighter than water, and an aqueous fraction. The two oil fractions are dehydrated and sent to filtration. The aqueous phase is cooled and recycled to the scrubbers. Hot char is discharged from Stage IV to a fluidized bed cooling step which generates high pressure steam. Recycled gas from Stage 1 is used to fluidize the cooling char (13).

Filtration--A flow diagram of the filtration and hydrotreating operations is shown in Figure 18. Oil from the product recovery system may contain some char particles which would plug the catalyst bed in the hydrotreating operation. These particles are removed by filtration. Hot filter cake consisting of char, oil, and filter aid is discharged to char storage. Filtered oil goes to the hydrotreating area.

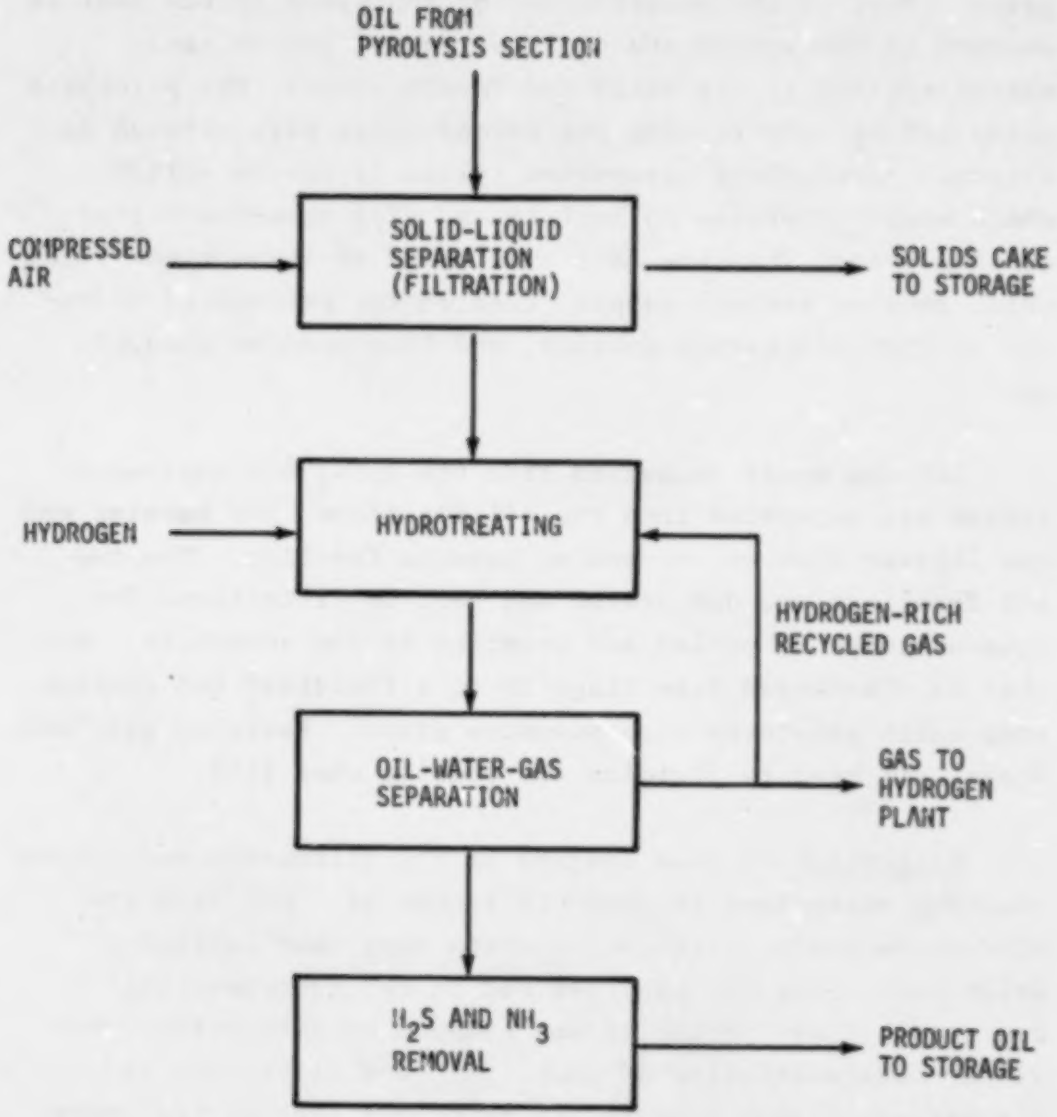

OIL FROM
PYROLYSIS SECTION
COMPRESSED AIR
SOLID-LIQUID SEPARATION (FILTRATION)
SOLIDS CAKE TO STORAGE
HYDROGEN
HYDROTREATING
HYDROGEN-RICH RECYCLED GAS
OIL-WATER-GAS SEPARATION
GAS TO HYDROGEN PLANT
H_2S AND NH_3 REMOVAL
PRODUCT OIL TO STORAGE

Figure 18. Oil separation and hydrotreating (13)

Hydrotreating--The filtered oil contains small amounts of sulfur, nitrogen, and oxygen as impurities. To improve its properties the oil is treated with hydrogen. This treatment also converts the impurities into hydrogen sulfide, ammonia, and water which are then separated from the product oil.

Material Inputs--

- Coal
- Steam
- Air
- Oxygen
- Catalyst
- Absorption solvent

Material Outputs--

- Synthetic oil
- Sulfur
- Ammonia
- Ash
- Spent catalyst
- Spent solvent
- Low-Btu gas
- Char
- Filter cake
- Pyrolysis gas
- Wastewater
- Tar
- Waste oil

Advantages, Disadvantages, and Efficiency--

In the COED process, coal is heated in several stages of fluidized beds at increasing temperatures. This enables the process to handle caking coals without the preoxidation or recirculation of char usually necessary to prevent agglomeration in the system. This feature permits the achievement of high yields of oil with minimum sized equipment. The aforementioned are the major advantages of the COED process. An additional advantage is that the process operates at low pressure, less than 70 kPa, which permits the use of conventional oil processing equipment (13).

The low pressure, multistage aspects of this process simplifies operation and maintenance. The countercurrent flow of coal and char to the gas and vapor flow helps to remove particulate matter, reducing the load on the scrubbing equipment. The process should integrate very well with a low Btu char gasification system such as Cogas.

However, the process does not remove pyritic sulfur from the char. This constraint would appear to limit the process to low sulfur coals if the char product is to be used for steam power generation without flue gas desulfurization.

Yields are about 588 kg of char, 0.175 to 0.263 m^3 of oil, 0.03 m^3 of liquor, and 250 to 312 standard cubic meters of 22.4 MJ/m^3 gas per metric ton of coal. On a weight percentage basis this is 60 for char, 19.6 for oil, 5.5 for liquor and 15.8 for gas.

Coalcon System

Background--

Union Carbide has been involved in coal conversion studies since 1936. The extent of this work includes operation of several pilot plants and a fully integrated 454-metric ton per day processing facility, which used a liquid phase catalytic hydrogenation process. The plant operated over a period of about six years in the mid 1950s. At the same time extensive research was carried out to convert coal to chemical products by pyrolysis of coal in the presence of hydrogen. The process, termed hydrocarbonization, was evaluated in an 18-metric ton per day pilot plant operation. A 4540-metric ton per day conceptual design was made in the mid 1960s but the economics did not favor chemical production via coal conversion, consequently, interest in the program waned (14).

In the early 1970s problems with petroleum supply caused Union Carbide to reevaluate its coal conversion experience. It was concluded that the hydrocarbonization route to convert coal to liquid fuels had potential application and a joint venture known as Coalcon was formed with Chemical Construction Corporation. In January, 1975, the Department of the Interior, through its Office of Coal Research, chose Coalcon to build and operate the Clean Boiler Fuels Demonstration Plant (14).

The preliminary design phase is near completion. DOE has reported that the economics are marginal and technical problems with the fluid bed carbonizer are greater than first believed. Latest reports indicate that only the design phase will be completed at this time and that additional research and development are required on the process.

System Description--

The Coalcon system is based on hydrocarbonization of coal. When heated in a hydrogen atmosphere, coal produces liquid, gaseous, and solid products. These materials are separated and treated to produce the final clean products. The solid material or char is then gasified with oxygen to produce a portion of the hydrogen-rich gas required for hydrocarbonization.

The system configuration is depicted in the overall process block flow diagram, Figure 19. The coal is washed, crushed, and stockpiled. The crushed coal is ground, dried, heated, and fed to the reaction zone using hydrogen as a carrier. Gases and vaporized liquids leaving the reaction zone carry some char particles. The vaporized liquids are condensed by contact with a recycled oil stream. These condensed liquids are separated into light and heavy fractions. The gas is treated to remove ammonia, hydrogen sulfide, and carbon dioxide. Sulfur is recovered from the hydrogen sulfide. The gas stream is separated cryogenically into a high purity hydrogen stream, a methanation synthesis gas stream, and a by-product liquefied gas fraction. The synthesis gas stream is processed to produce pipeline quality gas. The bulk of the char is removed from the bottom of the process (15).

Major Operations and/or Modules--

Sizing and drying--Figure 20 shows the coal preparation and handling operation. Coal is received, unloaded, and stockpiled. It then is crushed and ground to a particle size in the range of 250 to 44 μm. The coal is dried to about 1 percent moisture.

Hydrocarbonization--A flow sheet for the hydrocarbonization and product recovery operations is shown in Figure 21. The prepared coal is preheated and is injected into the reaction zone with pressurized hydrogen. In the reaction zone the temperature is 560°C and the pressure is 3.85 MPa. Other variables that affect the yield of products are residence time, partial pressure of hydrogen, and superficial gas velocity. Solid particles carried out by the gas stream are recovered and combined with the char (15).

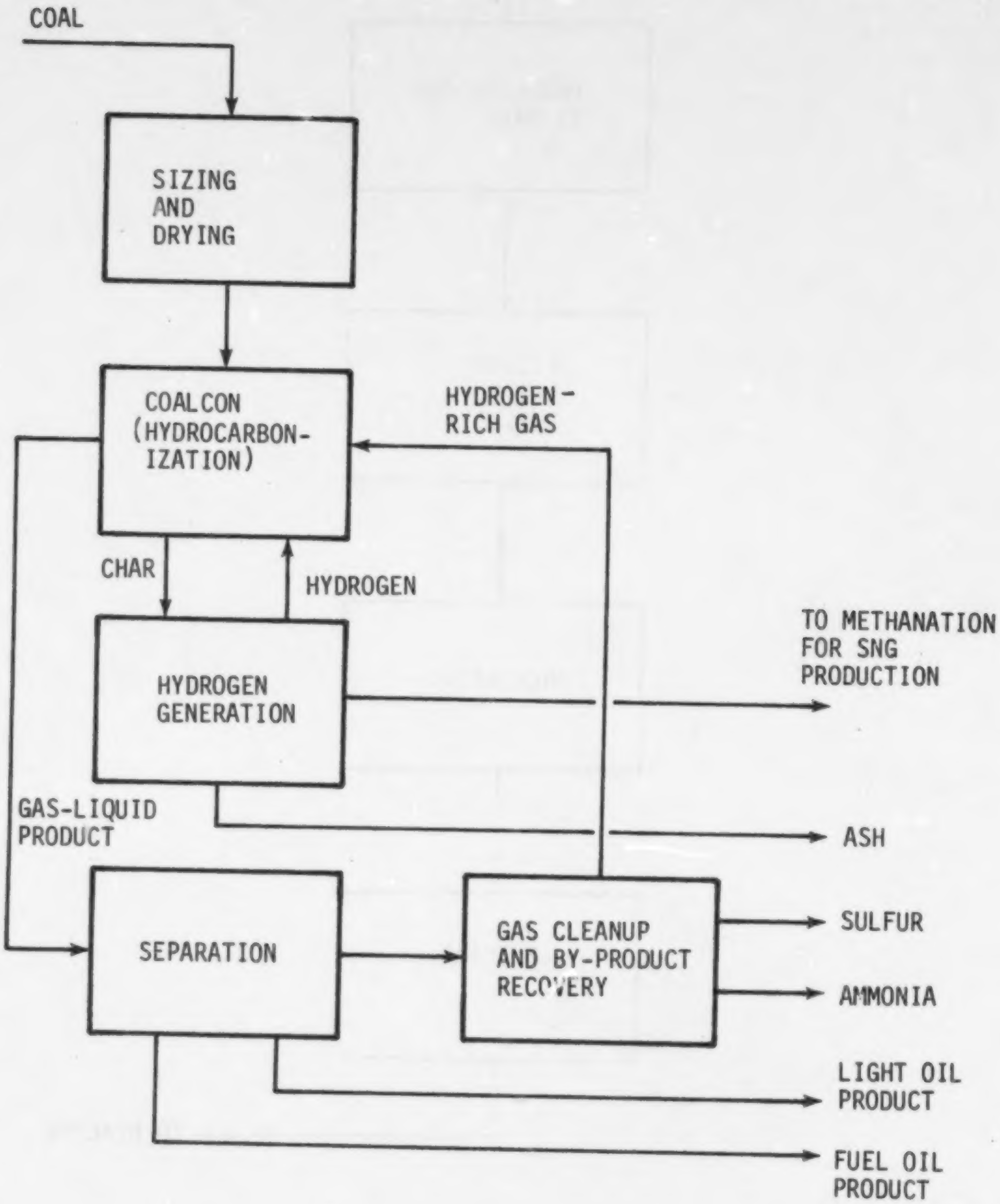

COAL
SIZING AND DRYING
COALCON (HYDROCARBONIZATION)
HYDROGEN-RICH GAS
CHAR
HYDROGEN
HYDROGEN GENERATION
TO METHANATION FOR SNG PRODUCTION
GAS-LIQUID PRODUCT
ASH
SEPARATION
GAS CLEANUP AND BY-PRODUCT RECOVERY
SULFUR
AMMONIA
LIGHT OIL PRODUCT
FUEL OIL PRODUCT

Figure 19. Coalcon system (15)

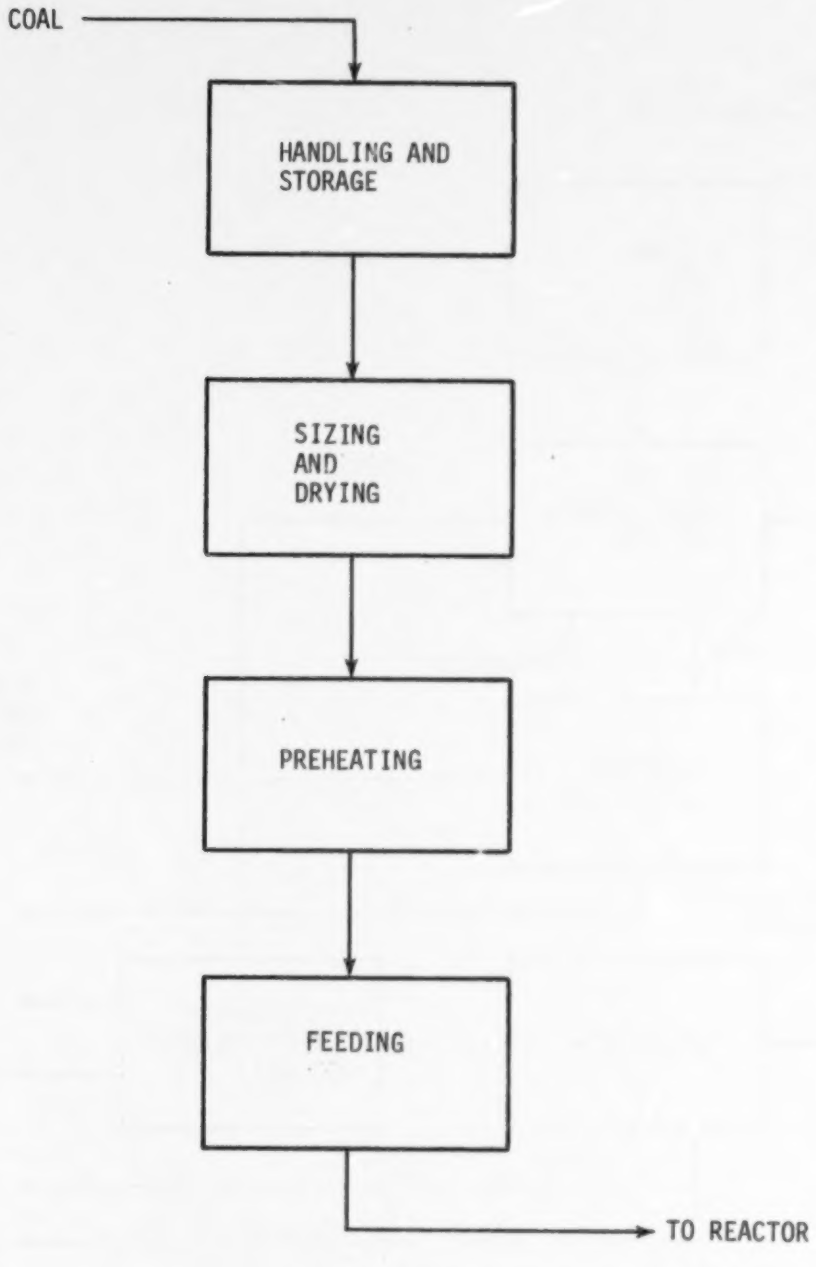

COAL
HANDLING AND STORAGE
SIZING AND DRYING
PREHEATING
FEEDING
TO REACTOR

Figure 20. Sizing, drying, preheating and feeding (15)

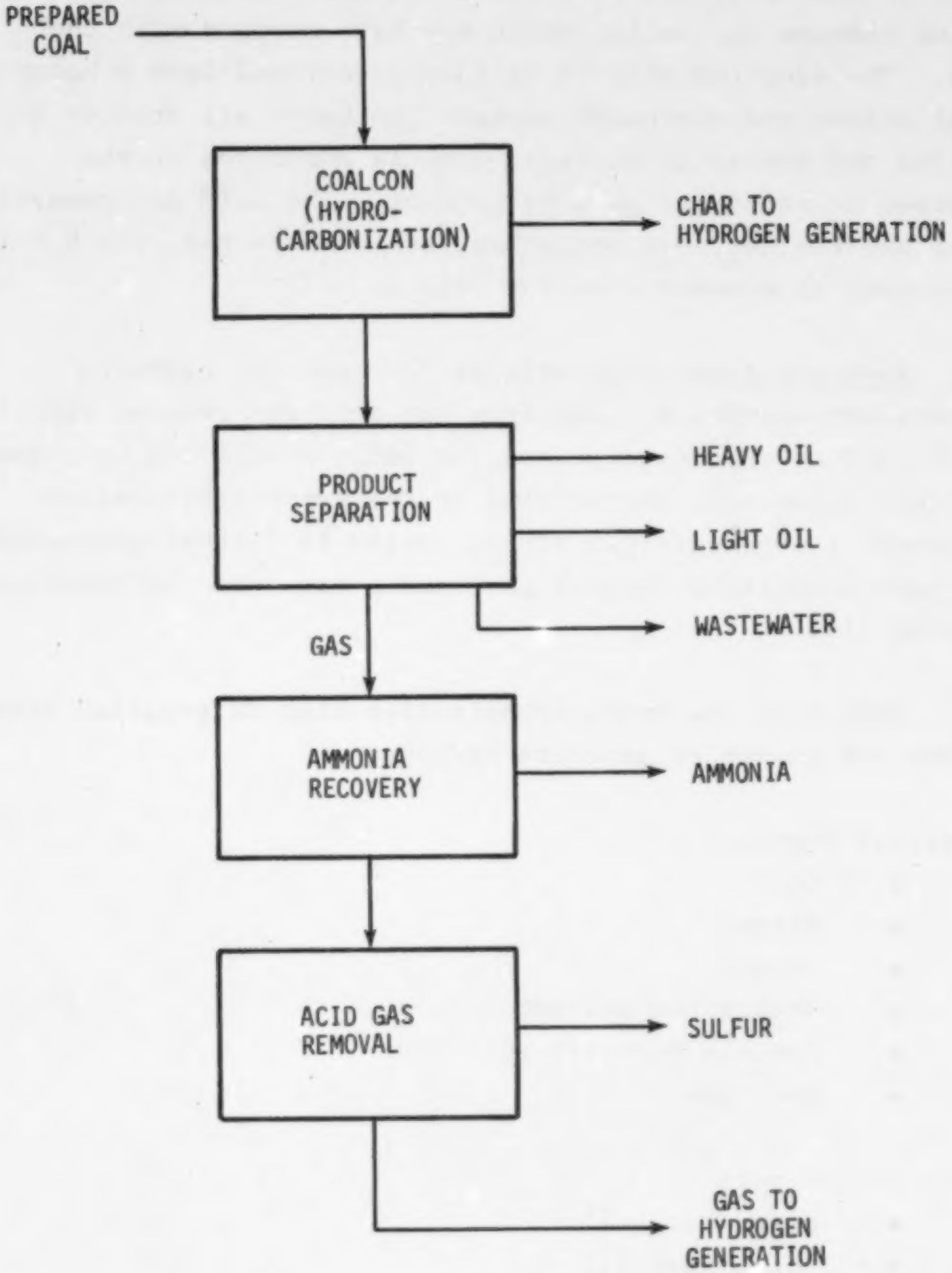

PREPARED COAL
COALCON (HYDRO-CARBONIZATION)
CHAR TO HYDROGEN GENERATION
PRODUCT SEPARATION
HEAVY OIL
LIGHT OIL
WASTEWATER
GAS
AMMONIA RECOVERY
AMMONIA
ACID GAS REMOVAL
SULFUR
GAS TO HYDROGEN GENERATION

Figure 21. Hydrocarbonization and product recovery (15)

Product recovery--The gas and vapors are separated into gas, light oil, heavy oil, and wastewater streams. A portion of the heavy oil is recycled to the scrubbing step which removes any solids which may have escaped with the gas. The recycled mixture is then fractioned into a heavy fuel stream and overheads stream. The heavy oil product is cooled and pumped to storage. Ammonia generated in the process is recovered as a by-product. The acid gas removal step absorbs CO_2, H_2S and aromatics from the gas. The H_2S is recovered as elemental sulfur (15).

Hydrogen generation--Figure 22 shows the hydrogen generation operation. Gas from the acid-gas removal step is processed by cryogenic separation into: a purified hydrogen stream, which will be recycled to the hydrocarbonization reactor; a synthesis gas stream, which is further processed to make substitute natural gas; and a liquefied hydrocarbon stream (15).

Char from the hydrocarbonization step is gasified with steam and oxygen to generate hydrogen.

Material Inputs--

- Coal
- Steam
- Oxygen
- Absorption solvent
- Ammonia recovery solvent
- Hydrogen

Material Outputs--

- Heavy fuel oil
- Light fuel oil
- Ammonia
- Sulfur

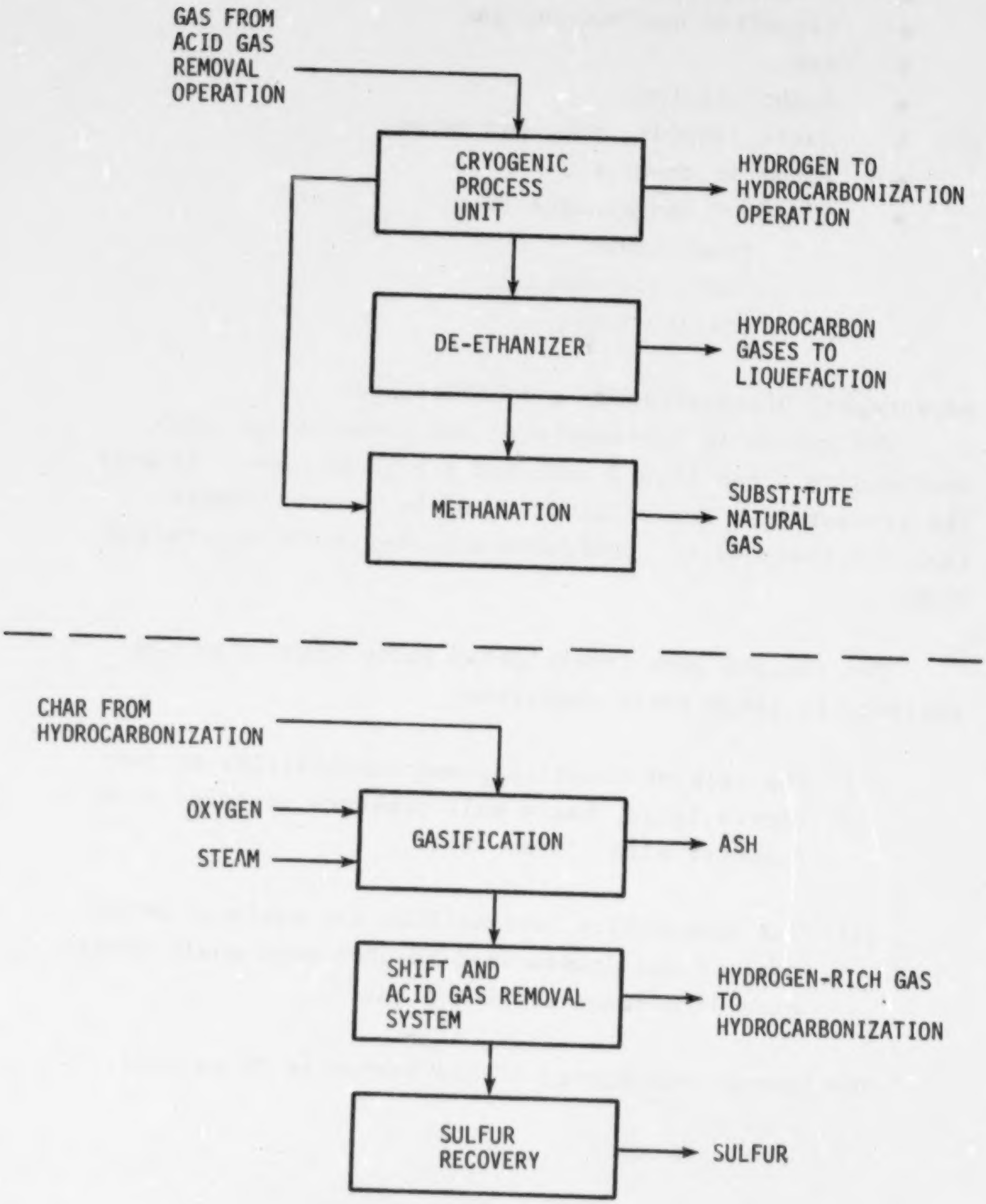

GAS FROM ACID GAS REMOVAL OPERATION
CRYOGENIC PROCESS UNIT
HYDROGEN TO HYDROCARBONIZATION OPERATION
DE-ETHANIZER
HYDROCARBON GASES TO LIQUEFACTION
METHANATION
SUBSTITUTE NATURAL GAS
CHAR FROM HYDROCARBONIZATION
OXYGEN
STEAM
GASIFICATION
ASH
SHIFT AND ACID GAS REMOVAL SYSTEM
HYDROGEN-RICH GAS TO HYDROCARBONIZATION
SULFUR RECOVERY
SULFUR

Figure 22. Hydrogen generation (15)

- Substitute natural gas
- Liquefied hydrocarbon gas
- Ash
- Spent catalyst
- Waste liquids, oil, and water
- Aromatic chemicals
- Blowdown and sludges from:
  - Power plant
  - Water treatment
  - Cooling tower

Advantages, Disadvantages, and Efficiency--

The system is non-catalytic and produces two main products, a clean liquid fuel and a high-Btu gas. Because the process is a dry, fluidized-bed hydrocarbonization reaction there is no formidable solids-liquids separation step.

Two factors were investigated which might pose constraints to large scale operation:

(1) The lack of facilities and capabilities to fabricate large, heavy wall pressure vessels, 9 mm in diameter with 150 mm walls

(2) The operability, reliability and scale-up potential of the pressurized reactor must await operation of a demonstration plant.

The thermal efficiency of the system is 70 percent.

Clean Coke Process

Background--

The United States Steel Engineers and Consultants, Inc., a subsidiary of United States Steel Corporation is developing a system to convert low grade, high sulfur coal to clean metallurgical coke, chemical feedstock, and liquid and gaseous fuels. The system, known as the Clean Coke Process, is sponsored by DOE. The Clean Coke system produces a variety of chemical feedstocks and metallurgical coke (2).

Laboratory and bench scale development studies on Illinois No. 6 Seam Coal have been underway since 1969. Various aspects including coal preparation, carbonization/desulfurization of coal in fluidized beds, and high pressure hydrogenation reactions have been the subjects of these investigations. Process development units have been built and are now operating. Two additional types of coal are scheduled to be processed. Information obtained from the PDUs will be used for the design of 218-metric ton per day pilot plant (2).

System Description--

The generalized flow diagram is shown in Figure 23. The process can be divided into carbonization and hydrogenation sections. Hydrogen required is produced within the process itself. The process design provides for operating the plant as a closed system (16).

Run of mine coal is dried, crushed, and ground. Approximately half of the prepared coal is conveyed to the carbonization section and the rest to the hydrogenation section.

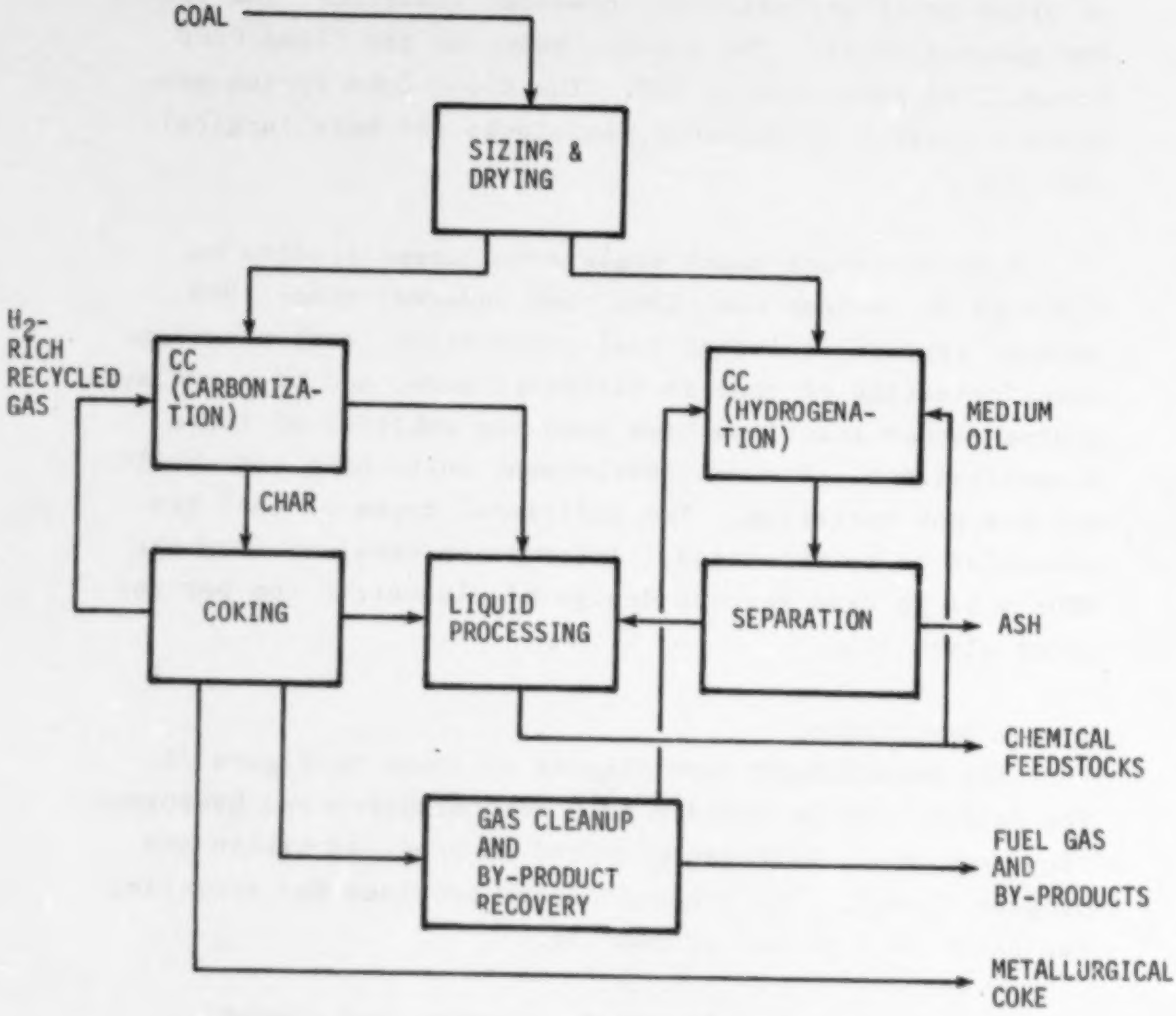

COAL
SIZING & DRYING
H_2-RICH RECYCLED GAS
CC (CARBONIZATION)
CC (HYDROGENATION)
MEDIUM OIL
CHAR
COKING
LIQUID PROCESSING
SEPARATION
ASH
CHEMICAL FEEDSTOCKS
GAS CLEANUP AND BY-PRODUCT RECOVERY
FUEL GAS AND BY-PRODUCTS
METALLURGICAL COKE

Figure 23. Clean Coke (CC) system (2)

In the carbonization section coal is pyrolyzed in a fluidized bed zone operating at temperatures of 705° to 760°C and pressures of 0.7 to 1.1 MPa. The fluidizing medium is hydrogen-rich recycled gas. The products from the carbonization section are char, a liquid stream which is directed to the liquid processing section, and a hydrogen-rich gas which is recycled back to the reactor. The char is pelletized with process derived heavy oil and the pellets are heated in the absence of oxygen to produce low sulfur metallurgical coke and a hydrogen-rich gas. Part of the gas is recycled to the carbonization step and the rest is sent to gas cleanup (16).

In the hydrogenation section prepared coal is mixed with a process derived oil to form a coal/oil slurry. The slurry is fed to a high pressure noncatalytic hydrogenation zone along with hydrogen from the gas cleanup section. The hydrogenation section operates at pressures of 20 to 30 MPa. The slurry feed is converted to a chemical-rich liquid and a gas, rich in light paraffins. These products are separated from the unconverted coal and mineral matter. Condensate from the vapor goes to a processing section where light, medium, and heavy oil are separated. Light oil is further processed to obtain chemical feedstocks, which include gasoline, benzene, naphthalene, and residual tars. Medium oil is used for slurry preparation. Part of the heavy oil is used in the pelletizing step, with the rest being fed to the carbonization section. Uncondensed gases are sent to the gas treatment section for separation into chemical feedstocks, which include ethylene and propylene, ammonia, sulfur, and fuel gas. Recovered hydrogen is recycled to the hydrogenation section (16).

Major Operations and/or Modules--

- Sizing and drying
- Carbonization
- Hydrogenation
- Product separation

Material Inputs--

- Coal
- Water
- Hydrogen

Material Outputs--

- Metallurgical coke
- Chemical feedstocks
- Ash and unreacted coal
- Waste liquids, oil and water
- Tar acids
- Tar bases
- Oil
- Organic chemicals
- Gasoline
- Sulfur
- Fuel gas
- Ammonia
- Hydrogen
- Blowdown and sludges from:
    - Power plant
    - Water treatment
    - Cooling tower

Advantages, Disadvantages, and Efficiency--

This system is unique among coal conversion schemes in that it offers as principal products metallurgical coke and aromatic chemicals, called petrochemicals. The capability of producing "clean coke" from low-grade, high-sulfur coals will help assure the basic steel industry of the United States an adequate supply of this essential raw material. This will reduce and eventually eliminate the present urgent search for coal deposits that are naturally suited to cokemaking. High yields of aromatics and olefins will help the short supply of chemical feedstocks. The design of the process provides for conducting all operations in closed systems (16).

During startup of the PDU some difficulties were experienced in operation of the carbonization step. Char produced by carbonization is converted to coke, thus eliminating the problem of char use and disposal. No mechanical separation equipment is used to separate the solids from the liquid product. Hydrogenation is non-catalytic and no external hydrogen is required. However, the hydrogenator operates at a very high pressure. A plant designed to process 5.9 million metric tons per year of coal would produce 2.0 million metric tons of coke pellets, 1.04 Tg of chemicals, 30 km^3 of liquid fuels and about 6.33 PJ of fuel gas.

TOSCOAL System

Background--

The Oil Shale Corporation (TOSCO), in cooperation with other private industries, has developed a process for retorting oil shale, known as the TOSCO II process. A semiworks facility was constructed at Grand Valley, Colorado to test the feasibility of the system. The capacity of this plant is 907 metric tons per day.

The technology of oil shale retorting has been applied to the low temperature carbonization of coal. A pilot plant for processing 22.5 metric tons per day of subbituminous coal has been operated at the Rocky Flats Research Center near Golden, Colorado.

Subbituminous coal has been processed, yielding a low sulfur char product of half the weight of coal with higher heating value than coal and low sulfur liquid fuel (17).

System Description--

The general flow diagram is shown in Figure 24. Run of mine coal received in the coal preparation and handling is unloaded, crushed, and stored in piles. The coal is then ground, dried, and preheated. The coal is partially devolatilized and fines carried over are removed from the vapors in a gas-solid separation system. The vapor is passed to a scrubbing system and the preheated coal is sent to a pyrolysis reactor. Here the coal is heated to carbonization temperatures of 425° to 535°C by contact with hot ceramic balls.

The char product leaves the pyrolysis zone and is subsequently cooled and sent to storage. Cool ceramic balls are returned to a ball heating system. Pyrolysis vapor is cooled to condense oil and water and to separate gaseous products. Oil and water are separated. The oil is distilled to yield gas oil, naphtha, and residuum. Uncondensed gas is used as fuel for heating the balls (17).

Major Operations and/or Modules--

- Sizing and drying
- Pyrolysis
- Product separation
- Gas purification

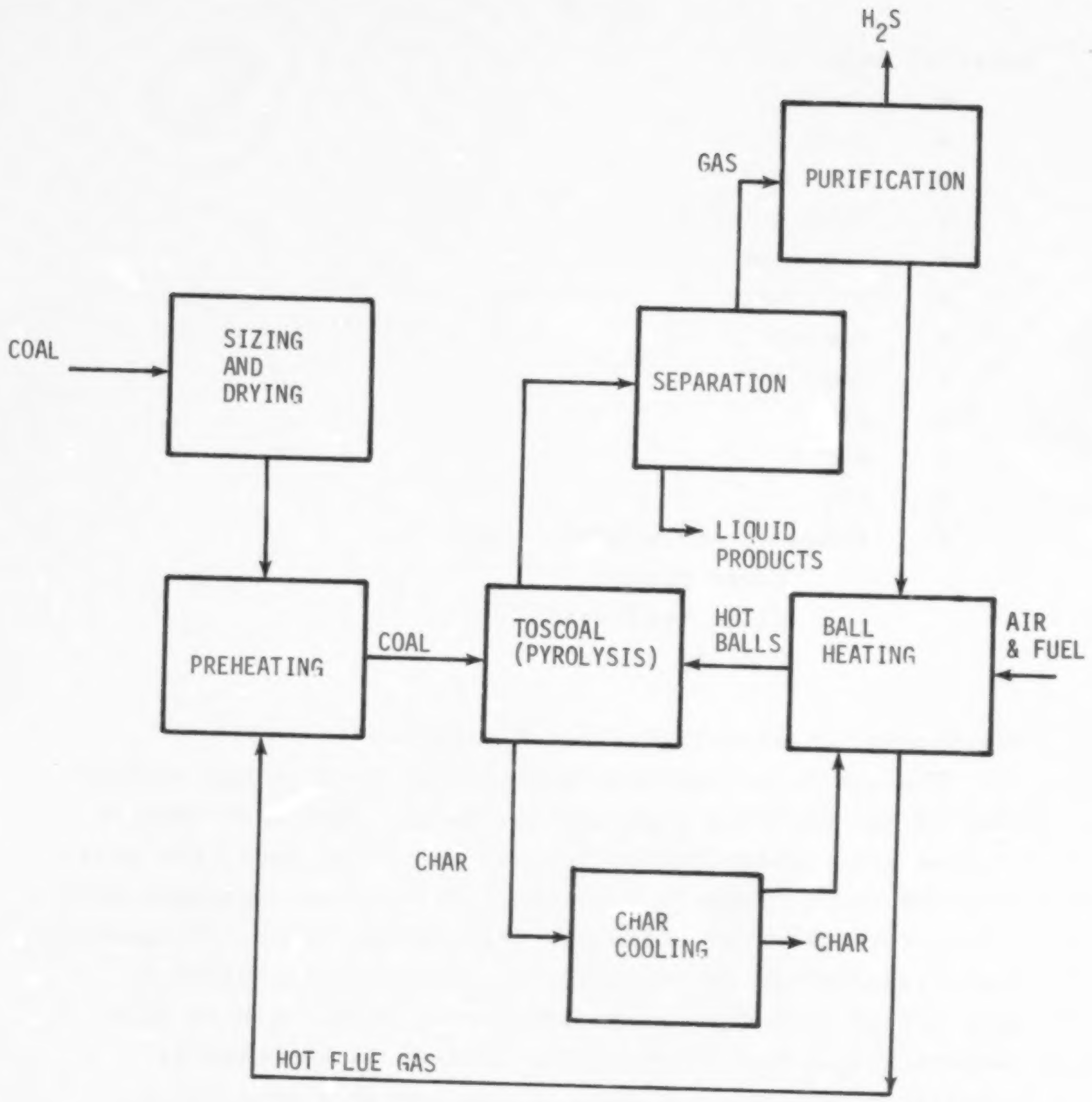

H_2S
GAS
PURIFICATION
COAL
SIZING AND DRYING
SEPARATION
LIQUID PRODUCTS
PREHEATING
COAL
TOSCOAL (PYROLYSIS)
HOT BALLS
BALL HEATING
AIR & FUEL
CHAR
CHAR COOLING
CHAR
HOT FLUE GAS

Figure 24. TOSCOAL system (18)

Material Inputs--

- Coal
- Air
- Water

Material Outputs--

- Char
- Fuel oil
- Fuel gas
- Wastewater
- Flue gas
- Naphtha
- Gas oil
- Coal dust
- Ash
- H_2S
- CO_2
- Blowdown and sludges from:
  - Power plant
  - Water treatment
  - Cooling tower

Advantages, Disadvantages, and Efficiency--

The use of an indirect heat source permits the production of gas having a high heating value. The char appears to have good possibilities for use as boiler fuel, for gasification and for making Formcoke. The process operates with a high throughput of solid per unit volume of retort, good heat transfer and moderate mixing. Pollution control is much better than for conventional coke ovens used in high temperature carbonization. The process is technically straightforward and has been proven operable on a large pilot scale. Hydrogen generation is not required and the system uses the generated flue gases for preheating the dry coal (17).

The product char is very dusty, highly pyrophoric, and not suited to conventional materials handling (17). The process has difficulty with caking coals unless they have been pretreated with steam and air before retorting. The system apparently possesses some mechanical complexities, which could contribute to high equipment and maintenance costs. Hauling and transfer of hot ceramic balls, which provide heat for pyrolysis, causes a major problem.

The yield is 0.05 to 0.09 m^3 of oil, 50 cubic meters of gas (heating value, 18.6 to 24.2 MJ/m^3) and 500 kg of char. This product mix compares least favorably with other pyrolytic processes in regard to the amount of liquids produced.

Occidental Research Corporation (ORC) System

Background--

Garrett Research and Development initiated a coal research program in 1969 to explore the feasibility of converting coal to liquid fuels. Garrett is a wholly-owned subsidiary of the Occidental Petroleum Corporation. Because of involvement in the petroleum industry, and the fact that conversion of coal to liquid fuel then appeared more economical than its conversion to gas, emphasis was placed on a study of coal liquefaction processes. Coal pyrolysis was selected from the alternatives because pyrolysis offered the simplicity and relatively low cost needed for rapid commercialization.

The initial laboratory scale results were quite encouraging and in 1971, a 3.6-metric ton per day pilot facility was constructed at LaVerne, California. Although built for the study of coal pyrolysis, during the first two years it processed solid waste materials only.

During this period, a variety of solid waste feedstocks were converted to liquid fuel oil. The pilot facility began processing coal in 1974. The operation has been relatively free of problems largely due to operating expertise developed during the solid waste program. Caking and noncaking coals have been successfully tested. Based on these results, a 227-metric ton per day municipal waste processing plant is being constructed in San Diego County.

The ORC Process is a solid phase hydrocarbonization process in which pulverized coal is almost completely converted to liquid and gaseous products in less than one minute. At 14.3 MPa and 500°C the yield is up to 30 percent distillable liquid, 40 percent tar, and the balance gas. The reaction is faster if a solution of ammonium molybdate is spread on the coal. Tests using a 15 percent stannous chloride catalyst indicate conversion in a few seconds to 55 percent liquid, 40 percent gas, and 5 percent tar. Coal feed size is about 74 μm. The fast reaction time should permit savings in capital costs for reactors (19).

A 227-metric ton per day pilot plant is being designed by ORC and the Commonwealth of Kentucky (20). Research and development on solid phase hydrocarbonization under a DOE contract is underway by Rocketdyne Division of Rockwell International at Canoga Park, California.

System Description--

ORC's coal pyrolysis system is being developed with the aim of maximum liquid yield. The process involves very rapid heating and devolatilization of pulverized coal in the absence of air, a short residence time in an entrained flow reactor, and a quick quench which prevents degradation of the liquid and gaseous products. Product distribution is strongly influenced by pyrolysis temperature, with lower temperatures favoring liquid formation. The pyrolysis products can be further refined and purified to obtain synthetic crude oil, char which is suitable for combustion in an electric utility boiler, pipeline gas, and elemental sulfur (19).

A general flow diagram is shown in Figure 25. Coal is first dried and pulverized as it would be for a utility boiler. The coal is then conveyed pneumatically with recycled product gas to the pyrolysis reactor. The reactor is an entrained flow vessel where recycled char is mixed with coal. Heated char provides the energy input for pyrolysis. The coal is heated to its decomposition temperature within one-tenth second at a reactor temperature of about 595°C. Volatile products are separated from char by cyclones and are rapidly quenched to avoid secondary decomposition. Part of the char is transported to a char heater where the temperature of the char is raised to about 650° to 870°C by adding a controlled amount of air at the bottom of the heater. The heater is also an entrained flow vessel and the short residence time inhibits formation of carbon monoxide, improving process thermal efficiency. Combustion gas from the heater passes through cyclones where unreacted char is separated and returned to the pyrolysis reactor (19).

The gases from the reactor are cooled and scrubbed to collect product tar. A portion of the gas stream is used to transport pulverized coal and heated char to the pyrolysis reactor. The rest is treated to remove acid gas and recover sulfur. The product gas can be upgraded to produce pipeline quality gas or it can be used as a hydrogen source for hydrotreating the tar product to a synthetic crude oil or a low sulfur fuel oil. Hydrotreating is carried out under pressure.

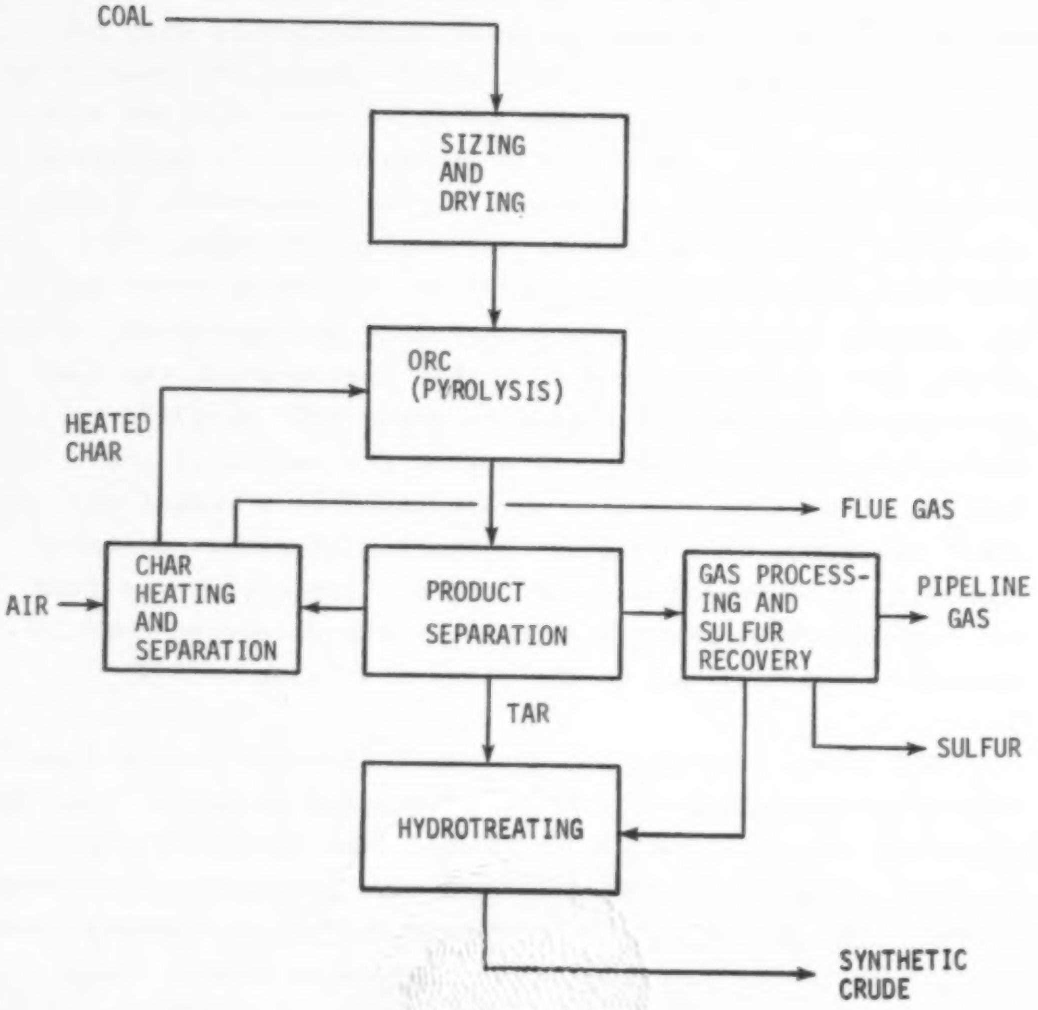

COAL
SIZING AND DRYING
ORC (PYROLYSIS)
HEATED CHAR
FLUE GAS
AIR
CHAR HEATING AND SEPARATION
PRODUCT SEPARATION
GAS PROCESSING AND SULFUR RECOVERY
PIPELINE GAS
TAR
SULFUR
HYDROTREATING
SYNTHETIC CRUDE

Figure 25. ORC system (19)

Remaining char, not passed to the char heater, can be used as a solid boiler fuel. The char is already dried and pulverized which offers an advantage over raw coal. Boiler modifications will be necessary due to the sulfur content of the char.

Major Operations and/or Modules--

- Sizing and drying
- Pyrolysis
- Product separation
- Hydrotreating
- Gas processing and sulfur recovery

Material Inputs--

- Coal
- Air

Material Outputs--

- Synthetic crude oil
- Char
- Sulfur
- Pipeline gas
- Flue gas
- Tar
- Tar acids
- Waste liquids, oil and water
- Coal dust
- Ammonia
- Blowdown and sludges from:
    - Power plant
    - Water treatment
    - Cooling tower

Advantages, Disadvantages, and Efficiency--

Tests to date indicate process conditions should allow the design of a small reactor because of the short residence time.

With high sulfur feed coals the char produced will contain too much sulfur to permit direct firing in utility boilers. Yields are about 59 percent char (27.9 MJ/kg) 33 percent oil and 6.6 percent gas of 26.1 MJ/m^3.

EXTRACTION

Supercritical Gas Extraction System

Background--

Two major problems facing advancement of coal liquefaction to commercialization are the operability of solid-liquid separation equipment and the high hydrogen consumption. The Supercritical Gas Extraction Process (SGE), now under development by the National Coal Board in England seems to have solved these problems. Catalytic, Inc., a subsidiary of Air Products and Chemicals, Inc. is evaluating the technical feasibility of this process for United States coals (21).

The solvent power of a gas or vapor increases with density; for a given gas at a given pressure the greatest density is obtained at its critical temperature. With proper conditions the level of supercritical extraction can be high, and increases of up to 10,000 fold in volatility of slightly volatile substances have been experienced. Therefore, if a gas or vapor is chosen having a critical temperature slightly below the temperature at which the extraction is to be carried out, it is possible to extract substances of low volatility at temperatures well below their normal boiling points. This principle has been used to extract liquids that are formed when coal is heated. The extractant gas can be recovered by reducing the pressure of the extracted liquid vapors and thereby separating them in solid form (21).

System Description--

A block diagram of the Supercritical Gas Extraction system is shown in Figure 26. Coal received from the mine is crushed, dried and pulverized to 74 μm size. The pulverized coal is fed to the extractor where it is mixed with recovered and makeup toluene and heated to about 395°C at 9.8 MPa pressure. Overhead vapors consisting of toluene, extract, water vapor, and hydrocarbon gases are cooled to condense solvent and extract. Uncondensed hydrocarbons are used as fuel gases. The condensed liquid product is flashed to separate solvent toluene and water vapor as overhead, from extract liquid product as bottoms. Toluene is separated from water and recycled to the extractor. Water is treated in the wastewater treatment unit. The residue in the reactor is removed mechanically, depressurized, and steam stripped to recover entrained toluene. The char can be used as fuel. The liquid extract product is fractionated to remove any remaining entrained toluene. The extract product which is rich in hydrogen and has low molecular weight can be readily converted to hydrocarbon oils and chemicals (21).

Major Operations and/or Modules--

The process includes the following major operations:

- Sizing and drying
- Supercritical extraction

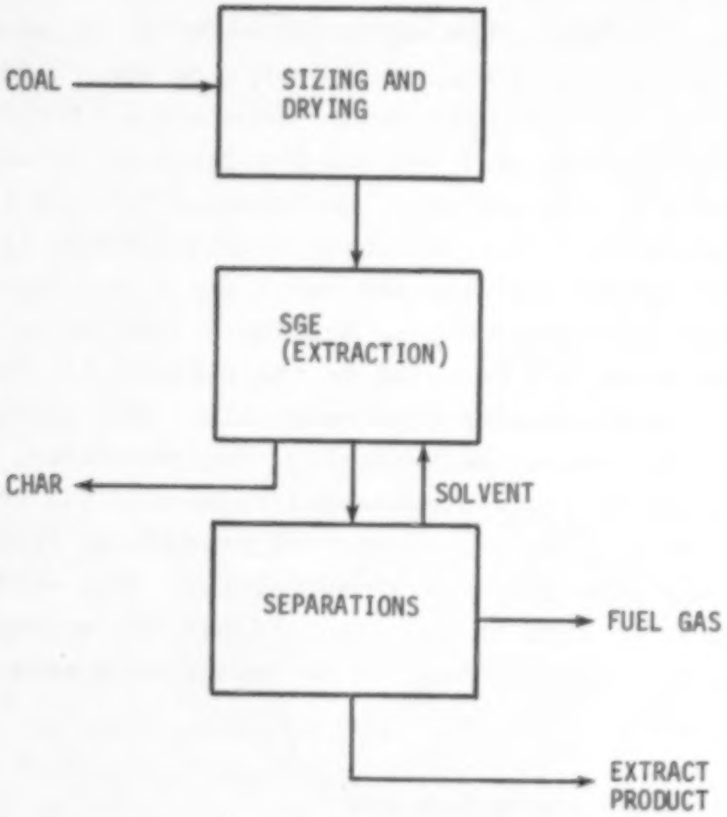

COAL
SIZING AND DRYING
SGE (EXTRACTION)
CHAR
SOLVENT
SEPARATIONS
FUEL GAS
EXTRACT PRODUCT

Figure 26. Supercritical Gas Extraction (SGE) system (21)

- Solvent and extract recovery
- Auxiliary facilities

Material Inputs--

- Coal
- Toluene

Material Outputs--

- Extract product
- Char
- Fuel gases
- Wastewater
- Flue gases
- Sulfur
- Ammonia
- Tar
- Tar acids
- Blowdown and sludges from:
    - Power plant
    - Water treatment
    - Cooling tower

Advantages, Disadvantages, and Efficiency--

No high pressure gas supply is required. The coal extracts contain more hydrogen and are of lower molecular weight than the products of other processes, thus facilitating their conversion to hydrocarbon oils and chemicals. The char or residue is a non-caking porous product having a significant volatile material content making it ideal for gasification. Products separate readily from the extractant since only solid and vapor phases are involved during extraction. Filtration of a high viscosity fluid is avoided (21).

The process produces more char than other liquefaction schemes. This would require that a commercial plant would need either a market for the char or facilities to convert it to gaseous fuels. Using toluene, up to one third of the coal feed has been extracted (21).

CATALYTIC SYNTHESIS

Fischer-Tropsch System

Background--

Interest in the synthesis of liquid hydrocarbons dates back to 1913, when patent applications described the reaction of hydrogen with carbon monoxide at high temperature and pressure and the hydrogenation of coal under pressure. In 1927 the hydrogenation of coal was undertaken on an industrial scale by I.G. Farben as a result of the development of catalysts with adequate activity and sulfur resistance. In 1922 Franz Fischer engaged in studies of the hydrogenation of carbon monoxide at low pressures with iron or cobalt catalysts activated by oxides of chromium, zinc, copper, and alkali metals. In 1925 at the Max Planck Institute, Franz Fischer and Hans Tropsch synthesized liquid hydrocarbons for the first time. Technical development of this synthesis was continued at Ruhrchemie beginning in 1934. The purpose, to produce motor fuel, was realized with an output of 675,000-metric tons per year from nine plants in Germany. An equal number of plants were built in other countries, many of which, however, were destroyed during World War II. Changes in the energy market and increasing coal prices discouraged the synthesis of motor fuels from coal. Conversion plants also required much maintenance, another detracting feature. With the decreasing interest in synthesized fuels, no new plants in Europe were started; in

1962 the last European plant, in Bergkamen, Germany, closed. However, in the Union of South Africa the situation was more conducive to coal based Fischer-Tropsch Synthesis. A Fischer-Tropsch plant was constructed near Johannesburg and began operation in 1955 (22). A second plant is now under construction in the Transvaal Region (23).

System Description--

Synthesis gas is produced by burning coal in pressure gasifiers in the presence of steam and oxygen, Figure 27. Other products, such as ammonia, phenols, carbon dioxide, hydrogen sulfide, naphtha, water, cyanides, various tar and oil components as well as numerous other impurities in minor amounts emerge from the gasifiers simultaneously with the desired constituents, hydrogen and carbon monoxide. The crude synthesis gas is fed to gas-purification units where the unwanted components are removed. The cleaned gas mixture is the raw material of feedstock for further processing by Fischer-Tropsch synthesis into liquid fuels and for the production of ammonia. The Fischer-Tropsch reaction uses a powdered iron catalyst which is recycled as an entrained bed. Feed gas with a H_2:CO ratio of 3.5:1 is passed through the catalyst bed where temperatures are in the range of 320° to 340°C and the pressure is 2.2 MPa.

Major Operations and/or Modules--

Sizing--The coal is crushed, ground, and wet screened. The minimum size feed that can be used is about 6 mm. Fines, about 25 percent, are used for steam generation.

Gasification and gas purification--The raw gaseous mixture formed by the reaction of coal with steam and oxygen is cooled and oil and tar are separated. The raw gas is further purified by scrubbing with methanol. The Fischer-Tropsch catalyst is very sensitive to sulfur, so the gas

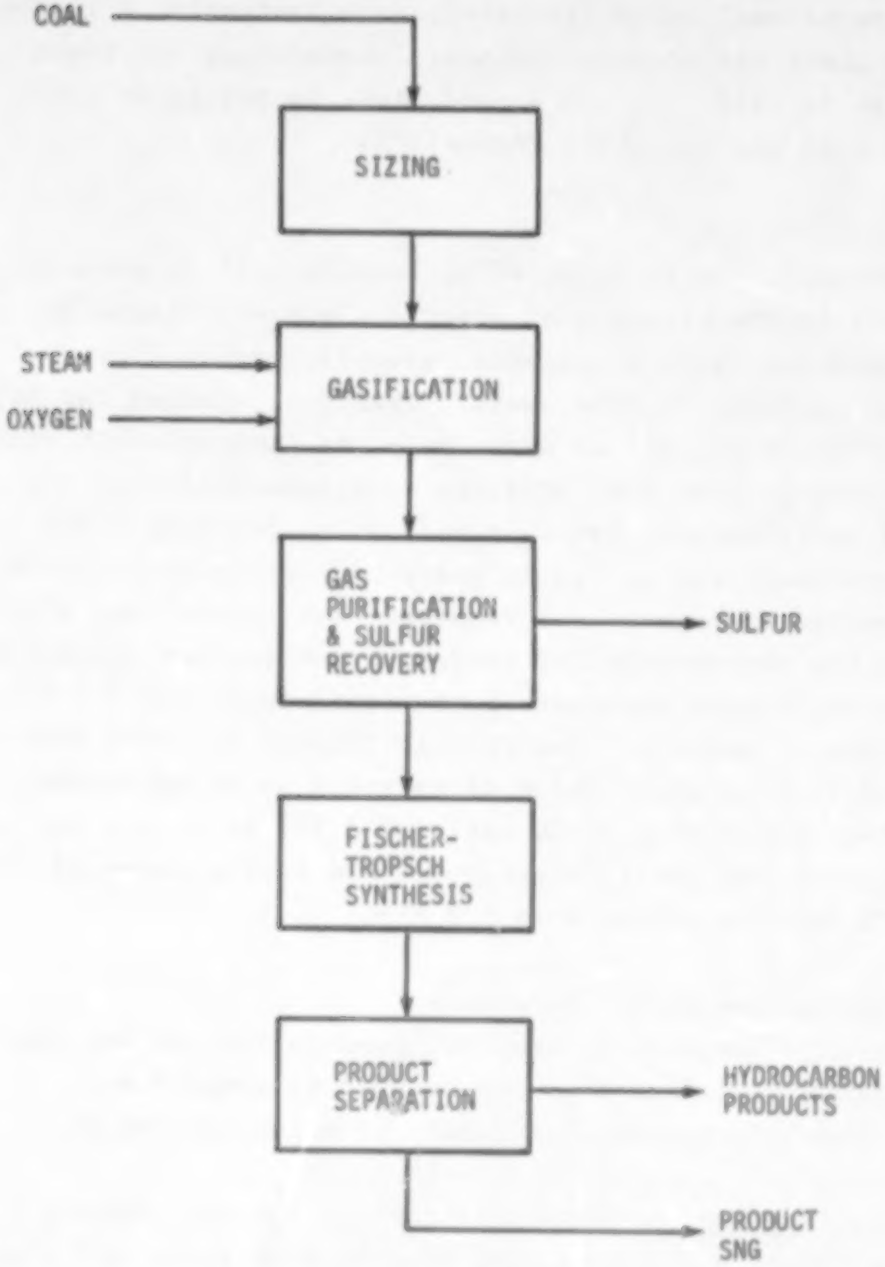

COAL
SIZING
STEAM
OXYGEN
GASIFICATION
GAS PURIFICATION & SULFUR RECOVERY
SULFUR
FISCHER-TROPSCH SYNTHESIS
PRODUCT SEPARATION
HYDROCARBON PRODUCTS
PRODUCT SNG

Figure 27. Fischer-Tropsch (F-T) system (5)

must be treated to remove all sulfur. The hydrogen to carbon monoxide ratio is adjusted by the CO shift reaction.

Synthesis--Fresh synthesis gas combined with recycled gas is fed to the reaction zone where it mixes with catalyst. A mixture of gases, vapors, and liquids is formed. These products must be separated from the catalyst, which must remain in the zone.

Product separation--Gas and vapors separate from the heaviest hydrocarbons in the reaction zone. Cooling causes vapors to condense from the product gas stream. These liquids are sent to the refinery for separation into the output products listed in Material Outputs. Part of the gas is used for recycling.

The product of the Fischer-Tropsch system is not a synthetic crude oil. It is a mixture of relatively simple hydrocarbons in a semi-refined state and is completely free of sulfur and nitrogen compounds (23).

Material Inputs--

- Coal
- Steam
- Oxygen
- Catalyst
- Methanol

Material Outputs--

- Fuel gas
- Propane/propylene
- Butane/butylene
- Gasoline
- Methylethyl ketone
- Light furnace oil

- Waxy oil
- Methanol
- Ethanol
- Propanol
- Butanol
- Pentanol
- Acetone
- Naphtha
- Waste acids
- Benzol
- Toluol
- Diesel oil
- Tar
- Creosote
- Ammonium sulfate
- Sulfur
- Spent catalyst
- Wastewater
- Waste oil
- Waste liquids, oil and water
- Blowdown and sludges from:
    - Power generation
    - Water treatment
    - Cooling tower
    - Gas reforming
- Ash and ash-conveying water

Advantages, Disadvantages, and Efficiency--

The process avoids the handling and treatment of high viscosity mixtures of tarry materials and mineral matter. It can produce a wide variety of products and is currently in commercial operation. The primary gasification step can be accomplished in commercially available gasifiers or in any of the various reactor configurations being investigated for low, medium and high-Btu gasification processes. It can use a wide variety of fossil fuel feeds, anything that can be converted to synthesis gas.

Since the conversion is a 2-step process more operations are required than in other processes. Heat removal from the synthesis step is a major problem. Plants now operating use a large number of small gasifiers. In addition the plants are difficult to operate, requiring much maintenance. The process yield is equivalent to about 0.54 m^3 per metric ton of coal. Conversion of the CO and H_2 entering the synthesis step is 85 percent.

Methanol System

Background--

Methanol was first produced commercially from wood. Natural gas, reformed to synthesis gas, is currently preferred for methanol production in countries where it is available as a cheap feedstock. Prior to the discovery of natural gas, solid fuels had been the major source of synthesis gas for methanol production. In Europe, Asia, and South Africa where natural gas was not available, coal became the primary source for synthesis gas. In countries where economics still favor this route, methanol is produced from coal.

In the United States natural gas is no longer readily available, hence alternate sources for synthesis gas are being evaluated. Abundant coal reserves in the United States may play an important role in synthesis gas production.

Some of the first generation systems that have been used to convert coal to synthesis gas are Koppers-Totzek, Lurgi and Winkler. The three systems employ different features and operating conditions, and each produces a gaseous product of different composition. A number of second generation processes are under development (24).

System Description--

Production of methanol from coal is a two stage process. In the first stage, coal is gasified to produce raw synthesis gas. The raw synthesis gas must be "cleaned" before it can be used for methanol synthesis. All extraneous compounds, other than H_2 and CO, must be removed. There is generally more CO than H_2 present in the raw gas; the ratio of H_2:CO must be adjusted to at least 2:1.

The methanol synthesis reaction is favored by high pressure, therefore synthesis gas from first generation gasification processes must be compressed. Other disadvantages of some first generation systems are the restriction to the use of non-caking coals and to particle sizes greater than 6 mm.

The second generation gasification systems produce better quality synthesis gas and require less treatment prior to methanol synthesis. They also operate at high pressures, eliminating the need for compression.

A block flow diagram of the system is shown in Figure 28. Raw coal from storage is crushed to a specific size and dried to a moisture content, depending on the type of gasification system. The coal is then preheated, if necessary, and conveyed to the gasification reactor. Steam and oxygen are injected and the coal is converted to a mixture of gases, liquids, and tars. The hot gases leave the reaction zone. A heat recovery system generates high pressure steam and heats boiler feedwater. Part of the steam is used in the process and the rest provides energy for product gas

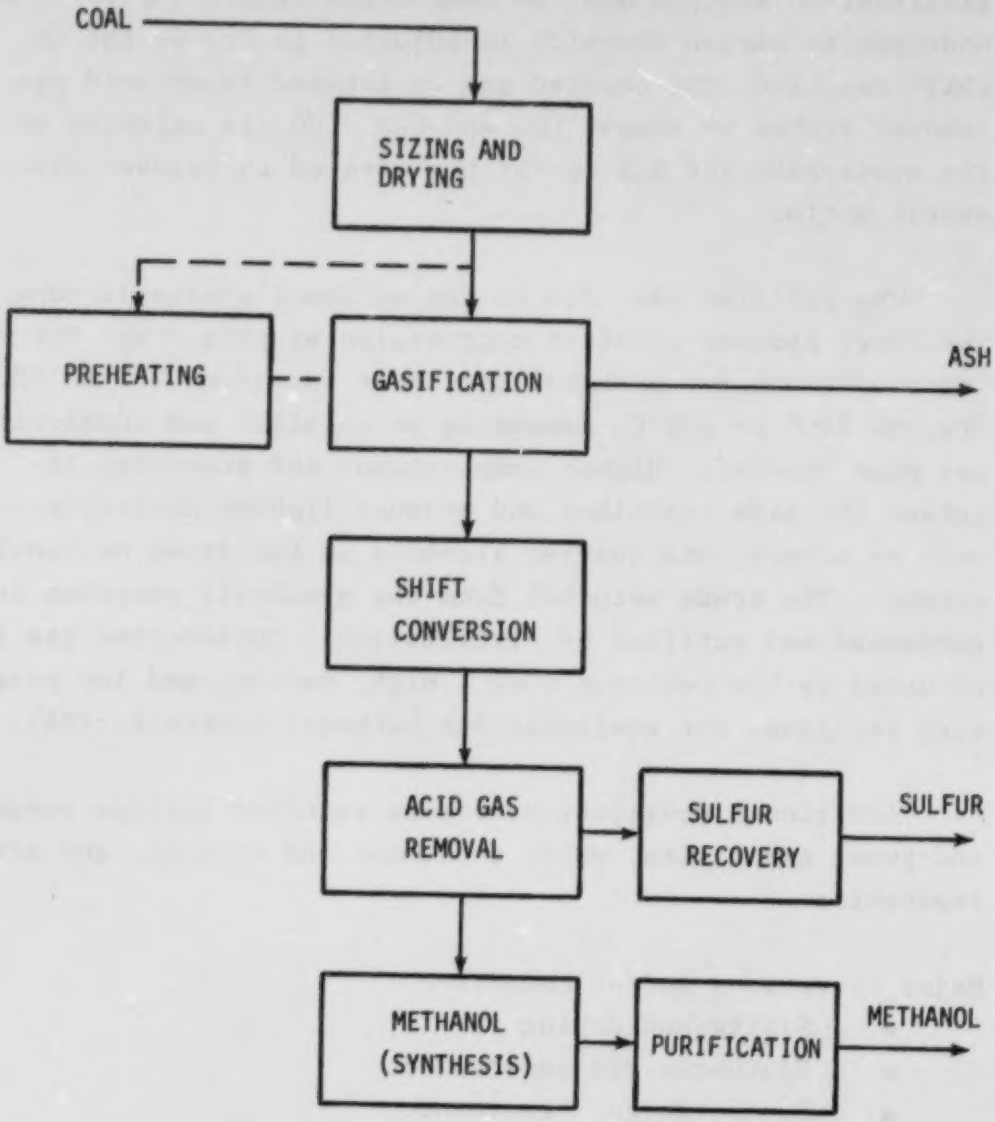

COAL
SIZING AND DRYING
PREHEATING
GASIFICATION
ASH
SHIFT CONVERSION
ACID GAS REMOVAL
SULFUR RECOVERY
SULFUR
METHANOL (SYNTHESIS)
PURIFICATION
METHANOL

Figure 28. Methanol system (24)

compression. Particulates carried out with the gas are removed by a separation system. Gas from the Lurgi gasification system requires processing to remove tars, heavy oils, and phenols. Gas from the Koppers-Totzek and Winkler gasification systems must be compressed before the ratio of hydrogen to carbon monoxide is adjusted to 2:1 by the CO shift reaction. The shifted gas is treated in an acid gas removal system to remove CO_2 and H_2S. CO_2 is rejected to the atmosphere and H_2S is further treated to recover elemental sulfur.

The purified gas goes to the methanol synthesis zone. The Lurgi process requires compression at this step. Operating conditions for methanol synthesis vary from 0.5 to 30.8 MPa and 260° to 426°C, depending on catalyst and conversion per pass desired. Higher temperatures and pressures increase the side reactions and produce lighter materials, such as ethers, and heavier alcohols in the crude methanol stream. The crude methanol from the synthesis reaction is condensed and purified by distillation. Unconverted gas is returned to the reaction zone. High, medium, and low pressure processes are available for methanol synthesis (24).

Additional auxiliary processes required include steam and power generation, water treatment and cooling, and air separation.

Major Operations and/or Modules--

- Sizing and drying
- Synthesis gas generation
- Synthesis gas treatment
- Methanol synthesis and purification

Material Inputs--

- Coal
- Water
- Air
- Oxygen
- Catalyst

Material Outputs--

- Methanol
- Ash
- Coal sludge
- Wastewater
- Sulfur
- Tars
- Heavy oils
- Tar acids
- Spent catalyst
- Coal dust
- Ammonia
- Blowdown and sludge from:
  - Power plant
  - Water treatment
  - Cooling tower

Advantages, Disadvantages, and Efficiency--

No new basic technology beyond coal gasification is needed to produce methanol from coal. The synthesis feed gas can be produced by many steam-carbon-oxygen coal gasification schemes. The new low pressure process for methanol synthesis uses copper base catalysts, is cheaper and in most cases it is used instead of the older classical high pressure process which used zinc and chromium oxide catalysts. The older methanol synthesis catalysts are readily positioned by sulfur compounds.

A material balance for a 4540-metric ton per day methanol facility shows hourly flow rates of 408 metric tons of process coal feed for 189 metric tons of methanol produced, or 2.15 units of coal per unit of methanol.

SECTION 2

SYSTEM OPERATIONS AND AUXILIARY PROCESSES

INTRODUCTION AND SUMMARY

Significant technical differences exist among the liquefaction processes. Many individual unit and processing steps are common to two or more systems, however. Furthermore, at the present stage of development, most published system designs are conceptual only; significant differences between the current design and future commercial plants are certain to arise.

To avoid the redundancy of studying each unit operation in each system, the unit operations have been grouped within functional modules. Each module performs a specific function, for example: hydrogenation, gas cleanup, coal preparation and hydrotreating.

These modules are composed of one or more individual unit operations or specific processes. Individual components of the module may vary slightly for different processes. However, because of the functional orientation, the streams entering and leaving a module will be essentially the same.

The major objectives of this section are the identification of waste streams originating in each module and of the technologies needed to control them. For this purpose, the modules have been defined and are individually discussed in this introduction. It has been noted where the module may serve the same function but with different exit streams. For the purposes of this section, process streams are defined as any stream entering a module and any stream leaving a module having as its destination another module (also called an output stream). Waste streams are defined as those streams leaving a module having as destinations either a control system or the environment.

These definitions are still undergoing some revision; therefore, future reports may present some modifications to those used here.

Systems Operations

Coal Pretreatment--

For purposes of this document, coal cleaning is assumed to have been done prior to receipt on site. Within the coal pretreatment operation there are modules to size, crush, grind, pulverize, and dry the coal and to prepare and preheat the slurry. Output streams include prepared coal, heated coal/oil slurry, particulates from mechanical operations, and stack gas from drying. Although no coal cleaning is performed, there may be a refuse stream. Specific processes in which slurrying and preheating is involved will have an additional stack gas stream as well as potential venting of gases.

Coal Liquefaction--

Hydrogenation--In these modules hydrogen is added to the "coal molecule." Portions of the coal which can be converted to soluble compounds dissolve leaving an insoluble carbon residue and mineral matter in suspension. Variations of the hydrogenation module include catalytic, non-catalytic, and donor solvent methods. Since these are usually carried out at high pressure, a pressure reducing step may be included. The crude liquid/solids leaving the reactor may be cooled using waste heat boilers or heat exchangers. There are only two output streams leaving the modules. These are the crude coal liquid and, in some systems, a gas stream. Occasional venting may occur, and periodic replacement of the catalyst will be necessary for catalytic processes.

Pyrolysis--High temperature gases are used to strip volatiles from and/or chemically add hydrogen to coal in this module. Pyrolysis uses steam and oxygen to react with the coal.

Vapor leaving the pyrolysis reactor is cooled by quenching with either water or oil. Non-condensibles are used elsewhere in the system. Waste heat recovery may precede the quench. The condensed liquid may contain an aqueous phase as well as particulates, and a separation step may be included. Output streams include the crude quenched liquid, non-condensible gas, char, water used to cool the char and excess quench water.

Hydrocarbonization--High temperature gases are used to strip volatiles from and/or chemically add hydrogen to the coal. Hydrocarbonization uses hydrogen to react with the coal.

Vapor leaving the hydrocarbonization reactor is cooled by quenching with either water or oil. Non-condensibles are used elsewhere in the system. Waste heat recovery may precede the quench. The condensed liquid may contain an aqueous phase as well as particulates, and a separation step may be included. Output streams include the crude quenched liquid, non-condensible gas, char, water used to cool the char and excess quench water.

Extraction--Under conditions which cause increased volatility, this module extracts fuel components of low volatility at temperatures below their normal boiling points, permitting their separation from mineral matter and other contaminants.

Catalytic synthesis--This module catalytically converts synthesis gas into liquid hydrocarbons or methanol. Functions are heating and pressurizing the feedstock, catalytic conversion, and cooling the raw product. A sulfur guard reactor may be used to protect the catalyst. Output streams are liquid hydrocarbons, hydrocarbon gases, water, spent catalyst, spent sulfur guard absorbent, and stack gas.

Separation--

Solids, liquids and gases are separated in numerous different steps. In coal liquefaction systems, situations arise involving two, three, and four phases. The phase separations are gas/solid, gas/liquid, liquid/solid, liquid/liquid, gas/liquid/solid, and gas/liquid/liquid/solid.

Modules include flashing and condensation, filtering, centrifuging, de-ashing, decanting, vacuum distillation, coking, and quenching. Output streams generally will be oils, carbon-containing residues, fuel gases, water, ash or slag, and tars or other heavy residuals.

Purification and Upgrading--

Fractionation--The fractionation module separates crude feedstock into product and by-product components. Primary steps used may be distillation, vacuum flashing, and stripping. In addition, heat must be supplied, depressurization may be necessary, and cooling is required. Output streams include products and by-products, recycled process solvent, fuel gases, solvents, water, liquid hydrocarbons, and solid or semisolid residues.

Hydrotreating--The purposes of hydrotreating are to remove sulfur, nitrogen, and oxygen compounds by conversion into hydrogen sulfide, ammonia, and water, and to further hydrogenate the crude oil. Hydrotreating, in this case an exothermic reaction, is a high pressure and high temperature process. Heat is supplied by plant fuel gas to preheat the crude. The reactor product is depressurized and cooled. An oil and an aqueous phase are formed. The oil is stripped to remove hydrogen sulfide and ammonia. Output streams include a sour gas stream from depressurization, the sour stripping stream, purified oil, stack gas, sour water, intermittent vents, and periodic catalyst disposal or regeneration.

Auxiliary Processes

Hydrogen/Synthesis Gas Generation--

Gasification, particulate removal, CO-shift, and gas cleanup are the major steps. In addition, there are quenching, cooling, and drying steps. Waste heat recovery is included (25). Output streams are synthesis gas; ash, slag, or char; water; particulates; carbon dioxide; hydrogen sulfide; and spent catalyst.

Oxygen Generation--

Requirements for oxygen are met by this process. Cryogenic separation of air is assumed. Electric or steam driven compressors provide the motive force and cooling water is required. Oxygen is the only process stream. Nitrogen, argon, and carbon dioxide are output streams, which may be recovered as by-products or be wastes.

Acid Gas Removal--

This process separates hydrogen sulfide from hydrocarbon gas streams. In some instances, carbon dioxide may also be separated. Steps in the primary section consist of one or more gas/liquid or gas/solid contacts, appropriate temperature and pressure adjustment, and demisting when necessary. Supporting steps are absorbent regeneration and makeup. Product gas, free of acidic constituents, is the main output stream. Other output streams are regenerator off gas, hydrogen sulfide, carbon dioxide and spent solid absorbent or solution.

Water Supply--

The function of this module is conditioning and purification of raw water for use as cooling water, boiler feed water, process and motive steam, and process water. Steps include standard chemical and physical water treatment techniques. Flocculation, pH control, deaeration, screening, filtering, and ion exchange are some potential methods. Output streams are water of varying degrees of purity, sludges, brines, and spent regenerant solutions.

Water Cooling--

This module includes cooling and conditioning of the plant cooling water. Evaporative cooling is assumed for heat removal. Chemical additives maintain cooling water quality. The output streams are cold water, cooling tower blowdown, evaporation, and drift.

Product Storage--

This module includes storage and shipment facilities. Only transfer operations are carried out. Process streams are the product and by-product materials. Intermittent and fugitive losses of vapors, liquids, and particulate may occur during loading and storage periods.

Sulfur Recovery--

The function of this module is the treatment of gaseous streams in which the concentrations of sulfur compounds are too high for discharge to the atmosphere. Such compounds are converted to elemental sulfur. Other output streams are carbon oxides, hydrocarbons, and sulfides. Examples of generic systems are the Claus and Stretford systems.

Wastewater Treatment--

This module separates pollutant materials from wastewater streams by physical, chemical and biological methods. Water quality is improved to the extent that the stream can either be reused or discharged to the environment.

Gaseous Waste Treatment--

This module separates and/or removes gaseous and vaporous components from waste streams. Such components may be either pollutants or by-products. Physical and chemical methods are employed. Components include compounds containing nitrogen, sulfur or carbon, organics, and ammonia.

Solid Waste Treatment--

This module provides for control of solids other than those which are airborne. Input streams are the solid waste materials from all modules. Major output streams will be ash, sludge and vacuum flash bottoms.

Particulate Recovery--

This module physically captures coal, ash, and other airborne solids some of which may be recycled or processed into by-products. Other output streams will be the cleaned gaseous components from which the particulate is removed.

Miscellaneous By-Product Recovery--

In addition to sulfur the range of by-products from coal liquefaction goes from syncrudes to naphtha and gas oils. These by-products with the exception of sulfur are amenable to petroleum refinery practices for their recovery. In addition phenol and/or ammonia will be present in the aqueous waste streams in recoverable amounts. Ammonia may be removed by air stripping, ion-exchange, and break-point chlorination. Phenols can be recovered by solvent extraction. Char, fuel oil, and fuel gases are other recoverable by-products. Hydrocarbon removal from liquid waste streams is best accomplished by steam stripping.

Steam and Power Generation--

This module produces process steam for heat and chemical reaction, steam for power generation, and steam for driving compressors, pumps, and other equipment. Steps are combustion of fuel, steam generation, and power generation. In most cases fuel will be plant fuel gas, but may be oil, char, or coal. Output streams are steam, electric power, stack gas, and boiler blowdown. If char or coal is burned, an additional stream will be ash.

Transient Waste Treatment--

Most discharges are anticipated but some are not. Such discharges are the result of accidents, leaks, and spills. This module provides the containment, treatment and disposal of these fugitive streams.

COAL PRETREATMENT

Crushing and Grinding

The coal as received may range in size from dust to large lumps. It is first crushed in a primary size-reduction step and then ground to a uniform small size, see Figure 29.

Pulverizing and Sizing

Coal ground to a small uniform size is pulverized in the final reduction step to reduce the bulk of the coal to the particle size range required for the process (see Table 1). A final sizing step consists of screening out the oversize particles which are recycled through the pulverizing steps.

Drying

The coal usually has a free moisture content which is too high for most processes (see Table 1). Hot combustion gases are used to dry the coal.

Slurrying and Preheating

The dried, sized coal may be used in this form as feed to the liquefaction operation or it may be mixed with recycled solvent to form a slurry which is then heated and used as the feed.

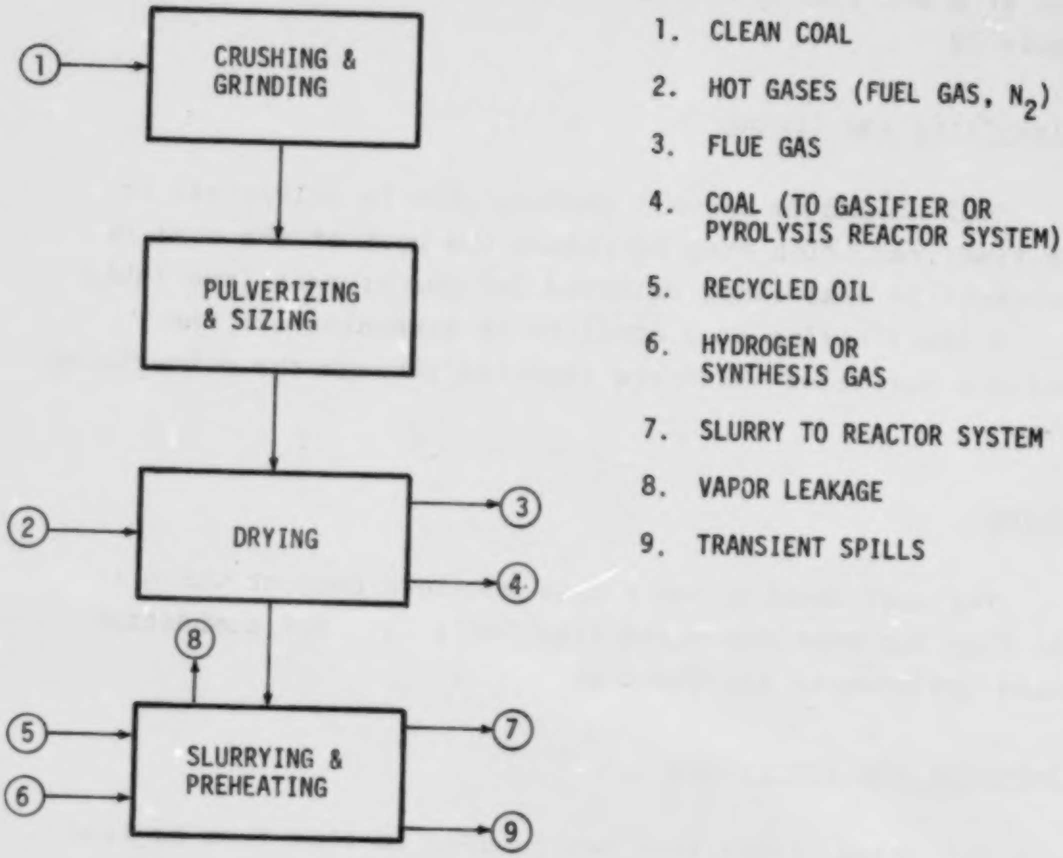

CRUSHING & GRINDING
PULVERIZING & SIZING
DRYING
SLURRYING & PREHEATING
①
②
③
④
⑤
⑥
⑦
⑧
⑨
1. CLEAN COAL
2. HOT GASES (FUEL GAS, N2)
3. FLUE GAS
4. COAL (TO GASIFIER OR PYROLYSIS REACTOR SYSTEM)
5. RECYCLED OIL
6. HYDROGEN OR SYNTHESIS GAS
7. SLURRY TO REACTOR SYSTEM
8. VAPOR LEAKAGE
9. TRANSIENT SPILLS

Figure 29. Modules in coal preparation operation

TABLE 1. PREPARED COAL CHARACTERISTICS

Process	Particle size, μm	Moisture, percent	Feed form	Feedstocks	References
Hydrogenation					
Synthoil	60% < 149	< 3.0	Slurry, oil	Lignite Subbituminous Bituminous	(1)
H-Coal	<420	0	Slurry, oil (33 wt% coal)	Lignite Subbituminous Bituminous	(4)
Bergius	<250	1.5	Slurry, oil (47 wt% coal)	Brown coal Bituminous	(5)
SRC	< 3200	< 3	Slurry, oil	Brown coal Bituminous	(7)
CO-Steam	< 149	20 to 30	Slurry, oil	Lignite	(8)
Exxon Donor Solvent	< 595	-----	Slurry, oil (33 to 50% coal)	Lignite Subbituminous Bituminous	(9)
CSF	< 1410	1	Slurry, oil (33 wt% coal)	Lignite Subbituminous Bituminous	(10)
ADL	80% < 74	-----	Slurry, oil	Lignite Subbituminous Bituminous	(11)
Liqui-Coal	<149	2	Slurry, oil (33 wt% coal)	Lignite Subbituminous Bituminous	(12)
Pyrolysis/ Hydrocarbonization					
COED	< 3200	6	Dry	Lignite Subbituminous Bituminous	(13)
COALCON	50% to 149	< 1	Dry	Lignite Subbituminous Bituminous	(14)
Clean Coke	-----	-----	Slurry, oil (for hydrogenation section) Dry (for carbonization section)	High volatile Bituminous	(16)
TOSCOAL	< 12700	-----	Dry	Subbituminous	(17)
ORC	-----	-----	Dry	Lignite Subbituminous Bituminous	(19)
Extraction					
Super Critical Gas Extraction	74	-----	Toluene	Bituminous	(21)
Catalytic Synthesis					
Fischer-Tropsch	Depends on the gasifier used for producing synthesis gas	Depends on the type of gasifier used for producing synthesis gas	Dry	Depends upon gasifier type	(22)
Methanol	Depends on the gasifier used for producing synthesis gas	Depends on the gasifier used for producing synthesis gas	Dry	Depends on gasifier type	(24)

Process Application

Crushing and grinding apply to all processes. As to pulverizing, the coal feed size requirements vary somewhat. In general the hydrogenation processes, both catalytic and non-catalytic, and the hydrocarbonization/pyrolysis processes use a larger particle size than the donor solvent processes. In processes where the coal is gasified for synthesis gas generation, such as Fischer-Tropsch and Methanol Synthesis, the coal feed size requirement will be determined by the gasification system used. Sizing applies to all processes and a drying stage is essential for almost all processes. The extent of drying depends on the process but generally the coal feeds are limited to less than two percent moisture. The COED process will accept a moisture content of up to six percent and CO-Steam up to 30 percent.

Feed to the liquefaction operation is either dry coal or a coal/oil slurry. Pyrolysis processes and those based on synthesis gas generation with few exceptions, use a dry feed system.

Materials Entering

The primary raw material is coal. Heated air, fuel gas, recycled solvent, nitrogen, hydrogen or synthesis gas, are also input streams. Rain, snow and other precipitation will be inadvertent inputs. Water used for washdown of equipment may be an additional input.

Conditions

Crushing, grinding and sizing are accomplished at ambient temperature and pressure. Pulverizing is accomplished at ambient conditions or at slightly elevated temperatures in a hot air stream to provide additional drying by taking advantage of the increased surface area. Mechanical dewatering for reduction of surface moisture is accomplished at ambient conditions. In thermal drying the dry product must be kept below its critical ignition temperature of 54° to 66°C to prevent spontaneous combustion. Otherwise an inert atmosphere must be used. Conditions for slurry formation are approximately 340°C and up to 446 kPa.

Equipment

- Crushers
- Conveyors
- Breakers
- Screens
- Grates
- Grizzlies
- Baghouses
- Precipitators
- Feeders
- Elevators
- Bins
- Dust collectors
- Chutes
- Vibrators
- Dryers
- Sump pumps
- Blowers
- Wet scrubbers
- Dry pulverizers
- Dry pulverizer gas preheaters
- Pulverizer dust collectors
- Coal dust scrubbers
- Dehumidifier heat exchangers
- Feeder to pulverizer chutes
- Inert gas blowers
- Slurry blend tanks
- Slurry blend tank mixers
- Slurry pumps
- Circulating pumps
- Sump pumps
- Slurry heat exchangers

Output Streams

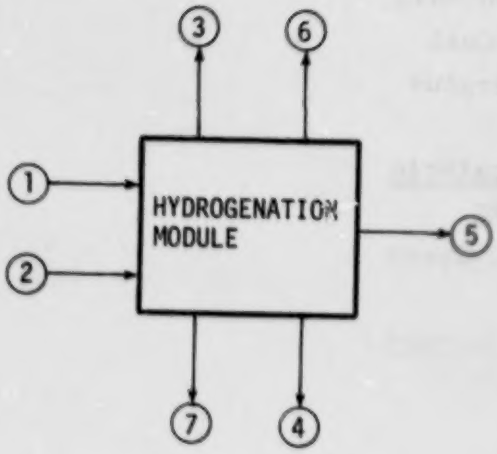
Outputs are dried, sized coal, slurry, fugitive coal dust, contaminated water, flue gas containing particulates, sulfur oxides, nitrogen oxides, carbon monoxide, hydrocarbons, aldehydes, ammonia, and hydrogen sulfide. Other potential environmental effects are noise and spontaneous ignition.

COAL LIQUEFACTION

Hydrogenation Modules

At high temperatures and pressures, coal reacts with hydrogen, yielding a mixture of liquid and gaseous compounds. The hydrogen content in coal is generally around 5 percent by weight while the carbon content is approximately 75 percent. If the hydrogen to carbon ratio is increased from 1:15 to approximately 1:9, the coal will be liquefied. Some processes such as H-Coal, Bergius, Synthoil, and Donor Solvent use catalysts, while others, including SRC and CO-Steam, use more extreme operating conditions or different reactants without an added catalyst. Products from processes generally include gases, and light and heavy oils. Most of these products require separation, filtration, condensation, or purification.

An example is the H-Coal process, Figure 30, in which the coal slurry is combined with makeup and recycled hydrogen. The mixture passes through a preheater and into the ebulliating bed catalytic reactor where hydrogenation occurs. Unreacted carbon, less than 5 percent, is removed from the reactor with some product oil. A portion of this slurry is returned to the reactor. After sulfur removal, a portion of the gas withdrawn from the top of the reactor is recycled to the reactor inlet. The remainder of the gas is used either as product gas or to supply fuel to the coal dryer, reactor preheater, and tail gas incineration on the Claus plant. After settling out large catalyst particles from the product oil, the bottom oil, with unreacted coal particles and ash, is separated by vacuum distillation and sent to the hydrogen manufacturing unit. Waste heat from the hydrogenation process is used to preheat fuel streams or to generate steam.


③
⑥
①
HYDROGENATION MODULE
⑤
②
⑦
④

1. COAL/OIL SLURRY
2. HYDROGEN
3. PRODUCT GAS
4. SPENT CATALYST (IF APPLICABLE)
5. REACTION PRODUCTS
6. VAPOR LEAKAGE
7. TRANSIENT SPILLS

Figure 30. Hydrogenation module in the H-Coal process.

Process Application--

- Catalytic
  - Synthoil
  - H-Coal
  - Bergius

- Non-catalytic
  - SRC
  - CO-Steam

- Donor Solvent
  - EDS

Materials Entering--

Process	Input materials	Added catalysts
Synthoil	Coal/oil slurry, hydrogen	Co/Mo/SiO_2-Al_2O_3
H-Coal	Coal/oil slurry, hydrogen	Co/Mo
Bergius	Coal/oil slurry, hydrogen	Iron oxide
SRC	Coal/solvent slurry, hydrogen	None
CO-Steam	Lignite/oil slurry, syngas or CO	None
Donor Solvent	Coal/solvent slurry, hydrogen	Not specified

Conditions--

Process	Pressure, MPa	Temperature °C	Residence time	Phase
Synthoil	14-27	450	Not specified	Liquid-solid-gas
H-Coal	20	455	Not specified	Liquid-solid-gas
Bergius	23-60	480	Not specified	Liquid-solid-gas
SRC	7-14	425-480	1-2 hours	Liquid-solid-gas
CO-Steam	21-27	380-400	1 hour	Liquid-solid-gas
Donor Solvent	10-18	370-380	15-240 minutes	Liquid-solid

Equipment--

The major process unit in each of the hydrogenation processes is:

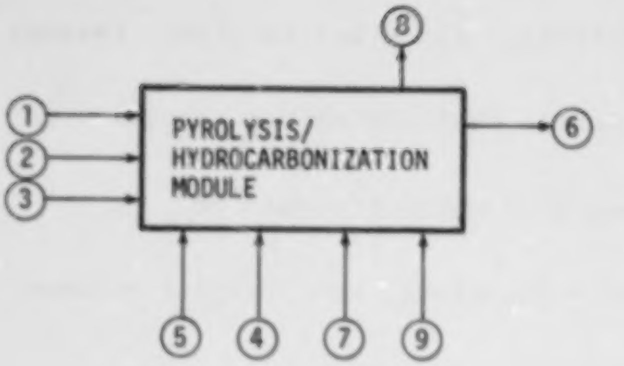
- Synthoil - fixed bed catalytic reactor
- H-Coal - ebulliating bed reactor
- Bergius - catalytic reactor
- SRC - dissolver, noncatalytic reactor
- CO-Steam - noncatalytic reactor
- Exxon Donor Solvent - ebulliating bed reactor

Output Streams--

- Process Streams
  - Reaction products
  - Recycled oil
- Waste Streams
  - Vapor leakage
  - Transient spills
  - Spent catalyst

Pyrolysis/Hycrocarbonization Module

This module is shown in Figure 31. When pyrolysis occurs, the large heterogenous coal molecule is broken down into a series of aliphatic and aromatic chemical compounds. This involves the formation and reassociation of free radicals and hydrogen units. It leaves a skeleton structure which is mainly carbon or coke. Hydrocarbonization is



8
1
2
3
PYROLYSIS/
HYDROCARBONIZATION
MODULE
6
5
4
7
9

1. COAL
2. CHAR
3. REDUCING GASES
   (HYDROGEN, SYNTHESIS GAS,
   ETC.)
4. STEAM
5. OXYGEN
6. RAW PYROLYTIC VAPORS AND GASES
7. CHAR AND ASH
8. VAPOR LEAKAGE
9. TRANSIENT SPILLS

Figure 31. Pyrolysis/hydrocarbonization module

similar to pyrolysis except that much more hydrogen is present causing the occurrence of more combinations of the free radicals with hydrogen than their reassociation with each other. This produces a larger proportion of liquid and gaseous hydrocarbons and less char.

Process Application--

- Pyrolysis
  - COED
  - Seacoke
  - TOSCOAL
  - Garrett (ORC)

- Hydrocarbonization
  - Coalcon
  - Clean Coke

Materials Entering--

- Coal
- Char
- Reducing gases
- Hydrogen-rich gas
- Water
- Heating medium
- Steam
- Oxygen
- Synthesis gas
- Hydrogen

Conditions--

Ranges for temperature and pressure are:

- Temperature: 175° to 815°C

- Pressure: 145 to 982 kPa

Equipment--

- Multiple-stage, fluidized-bed reactor
- Single-stage, fluidized-bed reactor
- Entrained flow reactor
- Quench tower
- Heat exchanger
- Cyclone
- Decanter
- Filter

Output Streams--

- Process Streams
  - Char
  - Raw crude oils
  - Coke
  - Hydrocarbon vapors
  - Pyrolysis gases

- Waste Streams
  - Ash
  - Particulates
  - Tar and tar acids
  - Aqueous condensates
  - NH_3
  - Flue gas
  - Coal fines
  - Cooling water
  - Quench water

Extraction Module

Gas extraction is a scientific principle which has been applied to coal conversion. It involves the extraction of liquid products formed when coal is heated. The technique permits the extraction of these low volatility liquids at temperatures well below their boiling points. The solvent capacity of a gas increases with its density. For any gas at a given pressure, its density will be greatest at its critical temperature. The extraction gas is therefore chosen so that its critical temperature is slightly below the temperature to which the extraction is to be carried out. Under these conditions the level of "supercritical" extraction can be high, and the volatility of a slightly volatile substance may be increased up to 10,000 fold. Using this technique, extractions of about one-third of the coal feed have been made. The remainder is recovered primarily as a solid char residue (see Figure 32).

Process Application--

The only process to which this module applies is the Supercritical Gas Extraction Process.

Materials Entering--

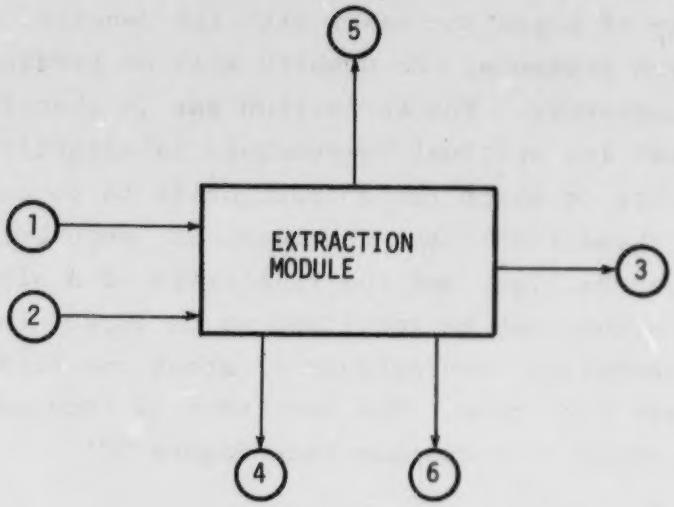
- Dry pulverized coal
- Toluene vapors
- Steam and water

Conditions--

Supercritical gas extraction, when using toluene as the extractant, is carried out under conditions of 400°C and 10 MPa.

Equipment--

- Feed lock hopper
- Extraction
- Residue-discharge lock hopper
- Quench tank
- Heat exchanger
- Degasser


5
1
EXTRACTION
MODULE
3
2
4
6

1. COAL
2. TOLUENE VAPOR
3. CRUDE EXTRACT, TOLUENE, AND GASES
4. CHAR
5. VAPOR LEAKAGE
6. TRANSIENT SPILLS

Figure 32. Extraction module

Output Streams--

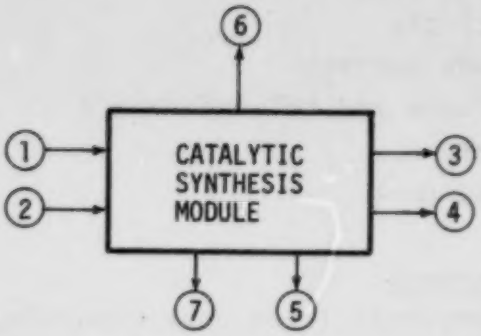
- Process Streams
  - Fuel gas
  - Crude extract
  - Toluene and toluene vapors
  - Char
  - Coal dust

- Waste Streams
  - Wastewater (from char quenching)

Catalytic Synthesis Module

Catalytic synthesis processes yield liquid hydrocarbon products by catalytically reacting hydrogen and carbon monoxide. Synthesis gas, produced from coal, cleaned, and then shifted to the appropriate H_2 to CO ratio, is used as feed to the reactor. Either hydrocarbon mixtures or methanol can be synthesized by proper choice of the process and catalyst. The catalysts are generally pyrophoric and sensitive to sulfur. Because of the sulfur sensitivity, synthesis gas feed must be sulfur free.

Typically, as seen in Figure 33, the gas mixture upon entering this module will be adjusted to the appropriate pressure and temperature. The hydrogen to carbon monoxide ratio also will have been adjusted prior to entering the catalytic synthesis module. A sulfur guard reactor, which contains a sulfur scavenger such as zinc oxide, will precede the catalytic reactor. In the catalytic reactor, hydrogen and carbon monoxide will react to form hydrocarbons and/or methanol. The catalysts used are either iron or copper based with appropriate promoters.


6
1
2
CATALYTIC SYNTHESIS MODULE
3
4
7
5

1. SYNTHESIS GAS
2. FRESH CATALYST
3. LIQUID PRODUCTS
4. SPENT CATALYST
5. WASTES
6. VAPOR LEAKAGE
7. TRANSIENT SPILLS

Figure 33. Catalytic synthesis module.

Following catalytic synthesis, condensation of the exit stream leaves liquid and vapor phases. These are separated and the vapor may be recycled or used as fuel. The liquid is depressurized, yielding a second vapor stream, which also may be recycled or used as fuel.

The remaining liquid is a mixture of the various byproducts of catalytic synthesis. The Fischer-Tropsch synthesis produces numerous hydrocarbon fractions, which, upon distillation yield fuel gases and oils, waxes, lubricants, solvents, and other organics, mostly paraffins. Methanol synthesis, in addition to producing methanol, yields some light hydrocarbons, heavier alcohols, and water. These latter products are separated by distillation.

Process Application--

- Fischer-Tropsch Synthesis (Arge, Synthol)
- Methanol Synthesis

Materials Entering--

- Synthesis gas (hydrogen to carbon monoxide ratio adjusted to appropriate values for specific product desired)
- Copper or iron based catalyst

Conditions--

- Temperature: 210 to 300°C
- Pressure: 2 to 5 MPa

Equipment--

- Compressor
- Heat exchanger
- Sulfur guard reactor
- Catalytic reactor
- Condenser

- Phase separator
- Flash expansion vessel
- Distillation column

Output Streams--

- Process Streams
    - Synthesis gas
    - Hydrocarbon noncondensibles, fuel, and recycled gas
    - Hydrocarbon liquid fuels, oils and waxes
    - Alcohols
- Waste Streams
    - Water from distillation - may contain hydrocarbons and alcohols (fuel oil) as contaminants
    - Spent copper or iron catalyst
    - Zinc sulfide

SEPARATION

Once coal has been liquefied in the reactor, the rest of the system consists of separations and purification of reactor products. All coal liquefaction systems require separation of one phase from another and separation of single phase products, which may include one or more of the following separations.

- gas/liquid
- gas/solid
- liquid/solid
- liquid/liquid
- gas/liquid/solid
- gas/liquid/liquid/solid.

The separation methods used in coal liquefaction technology are shown in Table 2.

The mixture of solids, liquids, and gases leaving the reactor is processed through various separation modules which can be grouped as: flashing and condensation; filtration; centrifugation; solvent de-ashing; vacuum distillation; coking; quenching and oil-water separation. They are shown in Figures 34 through 41.

Vapors produced in the reactor exit either as a separate overhead stream or as a combined gas/liquid/solid stream depending on reactor configuration and process operating conditions. In systems based on pyrolysis and hydrocarbonization the reactor products are a gaseous stream and solid char product. Vapors leaving the reactor as a separate stream are cooled to separate light hydrocarbons from uncondensable gases. Vapors are generally cooled by quenching with either water or oil.

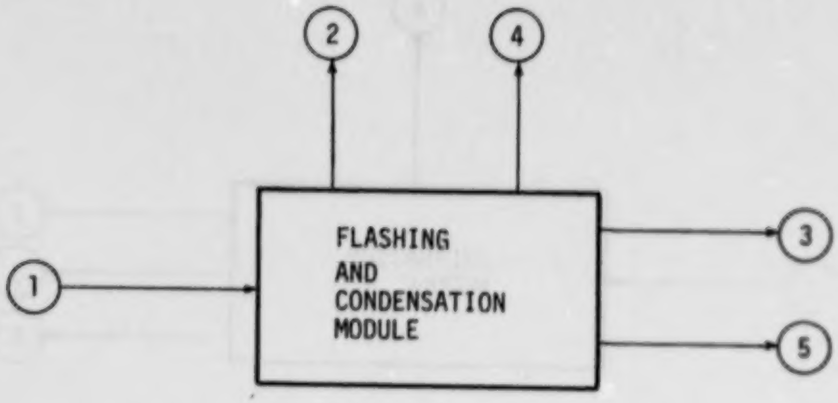
All liquefaction systems, except those based on synthesis gas, require separation of solids entrained in the liquid product. The solids consist of unreacted coal and mineral matter or char. Mechanical separation can be performed by filters, centrifuges and hydroclones. Solvent separation and products separation, mainly fractionation, are discussed later under Fractionation.

Process Application

Separation applies to all coal liquefaction processes.

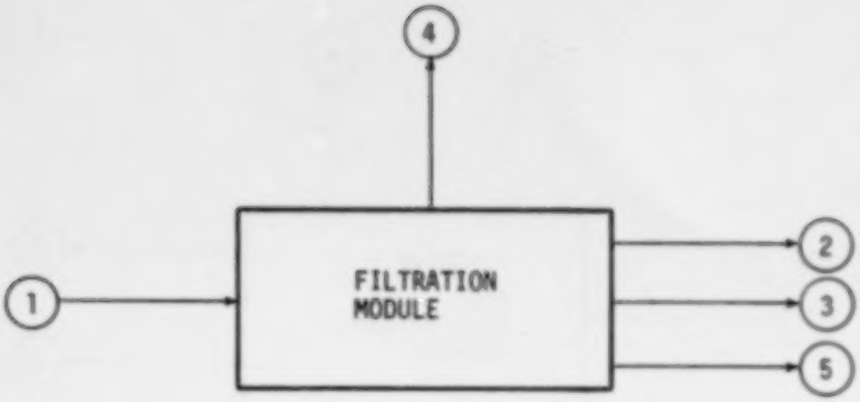
TABLE 2. SEPARATION METHODS FOR COAL LIQUEFACTION

Name	Feed	Separating agent	Products	Principle of separation
Equilibration separation methods				
1. Flash expansion	Liquid (slurry)	Pressure reduction	Liquid + vapor	Difference in volatilities (vapor pressure)
2. Vacuum/flash distillation	Liquid (slurry) and/or vapor	Heat	Liquid + vapor	Difference in volatilities
3. Stripping	Liquid (slurry)	Noncondensate gas	Liquid + vapor	Difference in volatilities
4. Solvent de-ashing	Liquid + solid	Solvent	Liquid + vapor	Precipitation by increasing particle size
5. Condensation	Liquid and/or vapor	Cooling	Liquid + vapor	Difference in volatilities
Mechanical separation methods				
1. Filtration	Liquid + solid	Pressure reduction (energy), filter medium	Liquid + solid	Size of solid greater than pore size of filter, medium
2. Centrifuge (filtration type)	Liquid + solid	Centrifugal force	Liquid + solid	Size of solid greater than pore size of filter, medium
3. Cyclone	Gas + solid or liquid	Flow inertia	Gas + solid or liquid	Density difference


2
4
1
FLASHING AND CONDENSATION MODULE
3
5

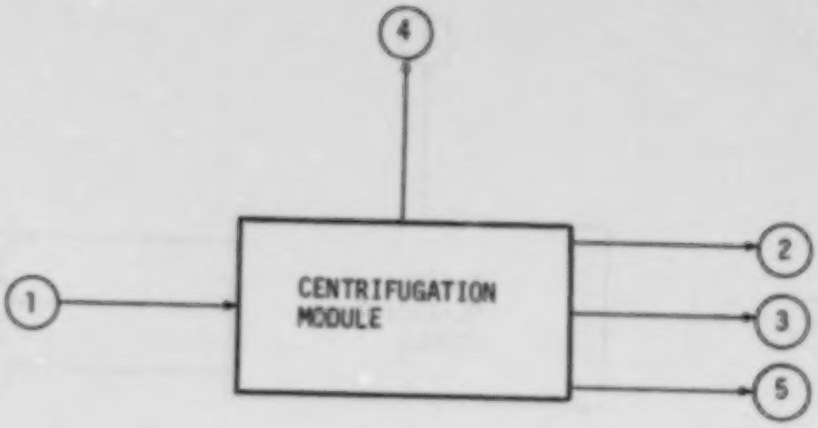
1. RAW COAL LIQUEFACTION PRODUCTS(S) GASES AND SOLIDS
2. UNCONDENSED GASES TO ACID GAS REMOVAL
3. RAW COAL LIQUEFACTION PRODUCT(S) AND SOLIDS
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 34. Flashing and condensation module


4
FILTRATION MODULE
1
2
3
5

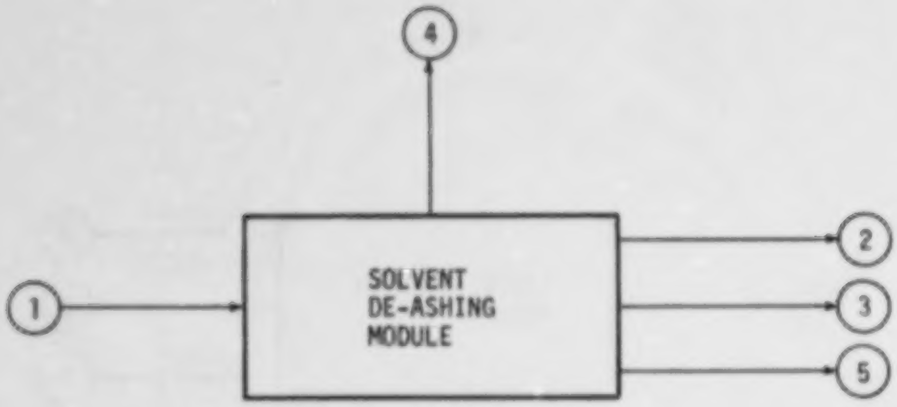
1. RAW COAL LIQUEFACTION PRODUCT(S)
2. SOLIDS-FREE LIQUID PRODUCT(S)
3. SOLIDS RESIDUE
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 35. Filtration module


4
1
CENTRIFUGATION MODULE
2
3
5

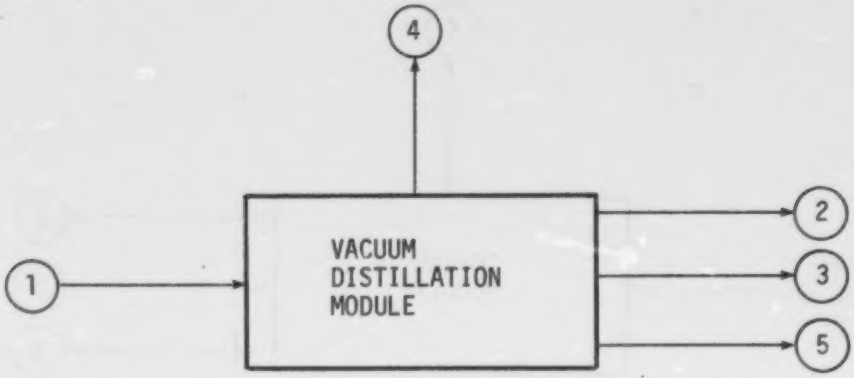
1. RAW COAL LIQUEFACTION PRODUCT(S)
2. SOLIDS-FREE LIQUID PRODUCT(S)
3. SOLIDS RESIDUE
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 36. Centrifugation module


4
SOLVENT
DE-ASHING
MODULE
1
2
3
5

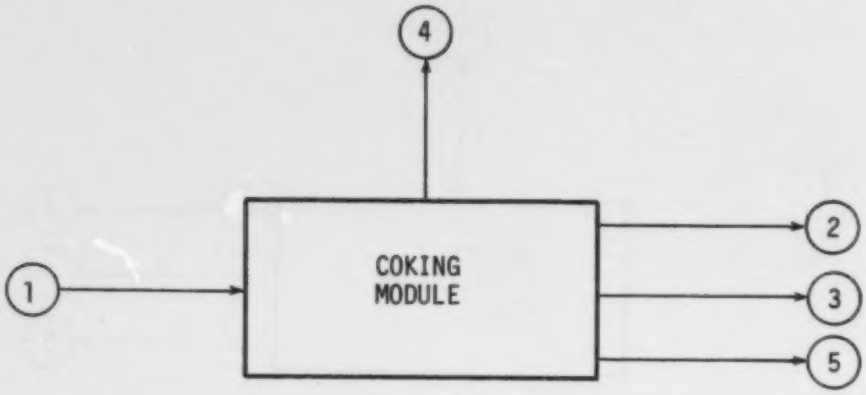
1. RAW COAL LIQUEFACTION PRODUCT(S)
2. SOLIDS-FREE LIQUID PRODUCT(S)
3. SOLIDS RESIDUE
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 37. Solvent de-ashing module


4
VACUUM DISTILLATION MODULE
1
2
3
5

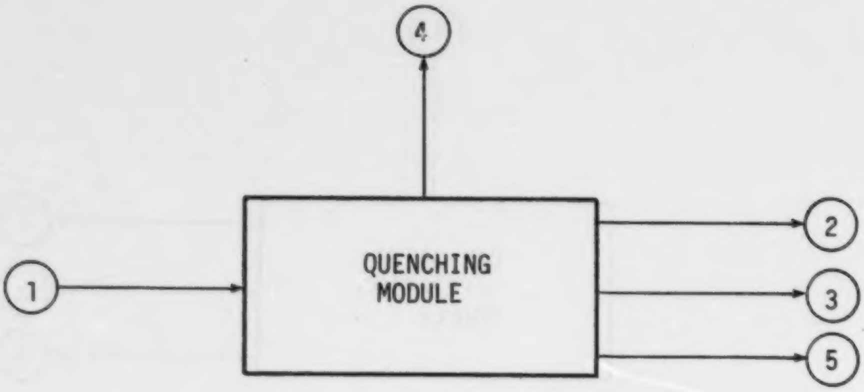
1. RAW COAL LIQUEFACTION PRODUCT(S)
2. SOLIDS-FREE LIQUID PRODUCT(S)
3. SOLIDS RESIDUE
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 38. Vacuum distillation module


4
COKING MODULE
1
2
3
5

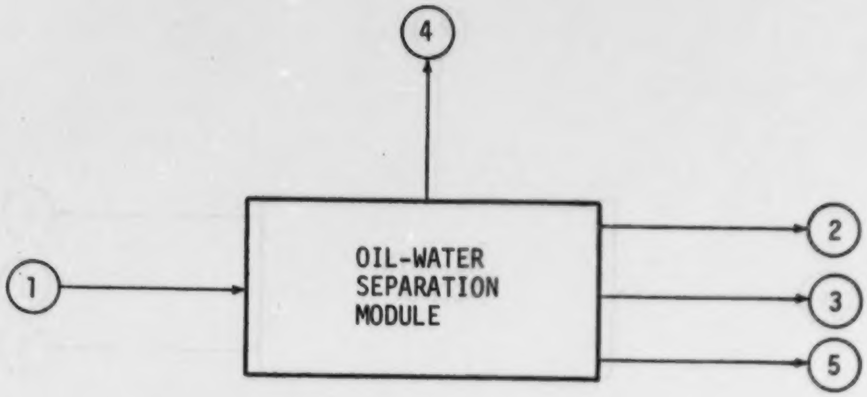
1. RAW COAL LIQUEFACTION PRODUCT(S)
2. SOLIDS-FREE LIQUID PRODUCT(S)
3. SOLIDS RESIDUE
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 39. Coking module


4
QUENCHING MODULE
1
2
3
5

1. RAW HOT GASES
2. UNCONDENSED GASES TO ACID GAS REMOVAL
3. LIQUEFIED PRODUCT(S) AND WASTEWATER
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 40. Quenching module


4
OIL-WATER SEPARATION MODULE
1
2
3
5

1. LIQUEFIED PRODUCT(S) AND WASTEWATER
2. PRODUCTS
3. WASTEWATER
4. VAPOR LEAKAGE
5. TRANSIENT SPILLS

Figure 41. Oil-water separation module

Materials Entering

- Unreacted coal
- Char
- Mineral materials
- Hydrocarbons
- Solvents
- Water
- Ammonia
- Hydrogen sulfide
- Hydrogen

Conditions

Temperatures range from ambient to reactor exit temperature. Pressures range from ambient to reactor exit pressure.

Equipment

- Hydroclones
- Filters
- Centrifuges
- Condensers
- Venturi scrubbers
- Decanters
- Vacuum/flash separators
- Flash expansion vessels
- Vapor strippers

Output Streams

Process Streams--
- Hydrocarbons
- Solvents

- Char
- Hydrogen

Waste Streams--

- Carbon residues
- Water containing ammonia, hydrogen sulfide, cyanide, tars, oils, particulates, ash and char
- Tars, heavy ends
- Phenols
- Vapors containing hydrocarbons, sulfides, sulfur dioxide, ammonia and particulates

PURIFICATION AND UPGRADING

Fractionation Module

Fractionation serves the dual purpose of recovering solvent and refining raw oil into fractions of specified boiling point ranges. The types of processes include prefractionation, atmospheric distillation, and vacuum fractionation. Prefractionation is a distillation process which separates light gases (C_1 through C_4) from the raw oil. Lower temperature and higher pressure conditions are used than for atmospheric distillation. Feed to the prefractionation column consists of raw oil and light hydrocarbons. Some water can also be carried over with the light hydrocarbons.

After prefractionation, atmospheric distillation can be used to separate the oil stream into:

- Light overhead products (C_4 and lighter)

- Naphtha or gasoline, middle oil having a boiling range of 38° to 205°C

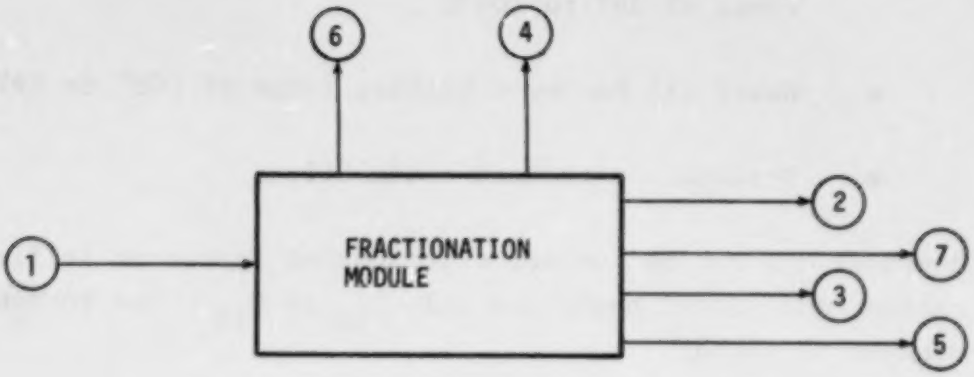
- Heavy oil having a boiling range of 205° to 297°C

- Residual or reduced crude oil.

Residual oil can be further fractionated in vacuum stills to recover additional heavy gas oil, C_{10} to C_{15}. The bottoms residue is pitch.

The light overhead product stream is cooled and the uncondensed gases are fed to the gas cleanup module. Condensed oil and water are separated in an oil/water separator. Middle oil can be boiled off as sidestream distillate cuts of kerosene, heating oil, and gas oil in a single tower or in a series of topping towers, each tower yielding a successively heavier product. Process solvent is distilled off at a temperature of about 260°C. In some processes the recycled solvent may be part of the product oil. The block diagram for the module is shown in Figure 42.

Process Application--
- Bergius
- SRC
- Coalcon
- Clean Coke
- Exxon Donor Solvent
- Consol Synthetic Fuel
- Arthur D. Little
- Liqui-Coal
- Methanol Synthesis
- Supercritical Gas Extraction


6
4
FRACTIONATION MODULE
1
2
7
3
5

1. RAW LIQUID PRODUCT, SOLVENT, WATER & LIGHT HYDROCARBONS
2. REFINED LIQUID PRODUCTS
3. WASTEWATER
4. UNCONDENSED GASES
5. BOTTOMS-PITCH, TAR, CARBON AND MINERAL MATTER
6. VAPOR LEAKAGE
7. TRANSIENT SPILLS

Figure 42. Fractionation module

Materials Entering--

- Process solvent
- Synthetic crude oil
- Process water
- Light hydrocarbons

Conditions--

Temperature ranges for different fractions of hydrocarbonization product liquid are:

Fraction	Temperature range °C
Light hydrocarbon gases	45 to 75
Benzene/toluene/xylene	75 to 130
Light oil	130 to 260
Middle oil	260 to 340
Heavy oil	340 at 1.33 Pa
Pitch	340 at 1.33 Pa

Equipment--

- Fractionation column
- Oil/water decanter

Output Streams--

- Process Streams
    - Benzene/toluene/xylene
    - Light hydrocarbons
    - Light oil
    - Middle oil
    - Heavy oil
    - Process solvent

- Waste Streams
    - Water containing phenols and dissolved organic matter

- Pitch containing unreacted carbon, mineral matter, tars and oils
- Uncondensed gases (H_2S, CO_2)

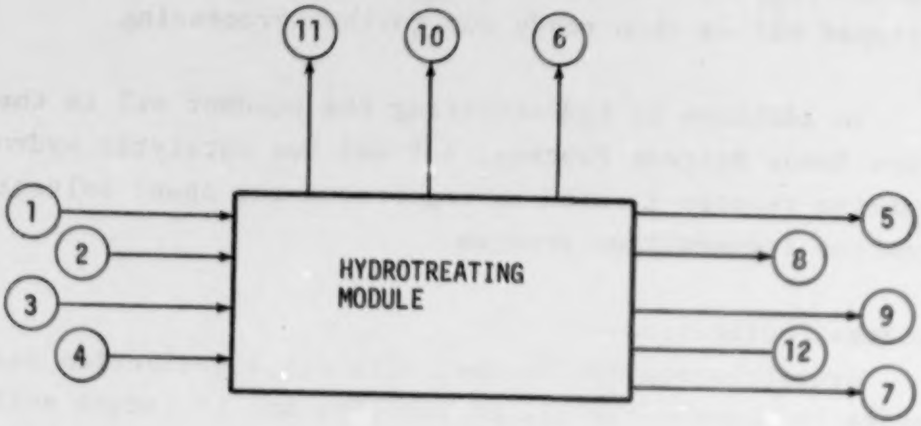
Hydrotreating Module

Hydrotreating is the treatment of liquid hydrocarbons (HC) with hydrogen under high temperature and pressure for purposes of purification and upgrading. This process converts the sulfur, nitrogen, and oxygen compounds contaminating the hydrocarbons to hydrogen sulfide, ammonia, and water. The hydrogen content of the hydrocarbons is increased through saturation reactions.

In a typical design, Figure 43, filtered oil and hydrogen are pumped, along with some recycled oil, through a gas-fired preheater into an initial catalyst guard reactor. The purpose of the guard reactor is to permit deposition of coke on low surface to volume packing, preventing plugging of the main hydrotreating reactor. From the guard reactor the gas-oil mixture is fed into a three section downflow hydrotreating reactor.

The hydrotreated product is cooled in a heat exchanger and fed into a high pressure flash drum where oil/water/gas separation occurs. Approximately 60 percent of the gas is recycled to the hydrotreaters. The remainder is sent to the hydrogen plant.

About half the separated oil is recycled to the hydrotreaters. The remainder is depressurized into a receiving tank, where water is separated from the product oil, and the oil is pumped into a stripping tower where clean product gas is used to strip the hydrogen sulfide and ammonia. The gas


11
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HYDROTREATING MODULE
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7

1. LIQUID PRODUCTS
2. HYDROGEN
3. FUEL
4. CATALYST
5. PRODUCT OIL
6. BY-PRODUCT GAS
7. WASTEWATER
8. SPENT CATALYST
9. COKE
10. FLUE GAS
11. VAPOR LEAKAGE
12. TRANSIENT SPILLS

Figure 43. Hydrotreating module

product from the stripper is sent to gas cleanup. The stripped oil is then ready for further processing.

In addition to hydrotreating the product oil in the Exxon Donor Solvent Process, a fixed bed catalytic hydrotreating reactor is used to regenerate the spent solvent from the liquefaction process.

Process Application--

Hydrotreating can be used with all liquefaction processes to upgrade the oil to gasoline and to reduce sulfur content. However, it is an essential part of COED, ORC, and Exxon Donor Solvent processes.

Materials Entering--

- COED - Filtered product oil, hydrogen makeup from hydrogen plant, stripping product gas, cobalt/molybdenum or nickel/tungsten sulfide catalyst

- ORC - Tar product, hydrogen from product gas, catalysts

- Donor Solvent - Spent solvent from liquefaction separation, hydrogen from hydrogen manufacturing, cobalt molybdate catalyst.

Conditions--

Process	Pressure	Temperature	Phase
COED	13.8 to 20.6 MPa	400° to 427°C	Liquid-gas-solid
ORC	"Under pressure"	Not specified	Liquid-gas
Exxon Donor Solvent	Not specified	Not specified	Liquid-gas

Equipment--

Typical hydrotreating process	Donor Solvent
Preheater	Fixed bed catalyst
Catalyst guard reactor	Liquid gas separator
Three section downflow catalytic reactor	Preheater
Stripping column	Stripping column

Output Streams--

- Process Streams
  - Syncrude
  - Naphthalene
  - Bleed gas
  - Contaminated gas
  - Coke

- Waste Streams
  - Normal Operating Conditions

    Wastewater: containing NH_3, H_2S, tars, phenols, BTX, organic sulfur compounds and traces of hydrocarbons such as naphthalene, dihydroxpyrene, dibenzofuran and acenaphthene/biphenyl.

    Preheater flue gas: containing nitric oxides, and carbon monoxide.

  - Periodic Discharges

    Gas with NH_3, H_2S and spent catalyst (heavy metals, metal carbonyls, and sulfides, during catalyst removal.

    Gas with particulates, NH_3, H_2S during catalyst replacement.

AUXILIARY PROCESSES

This category covers those processes associated with coal liquefaction but used for purposes incidental to the main functions involved in the conversion of coal to liquid products. It includes utilities supply and environmental control.

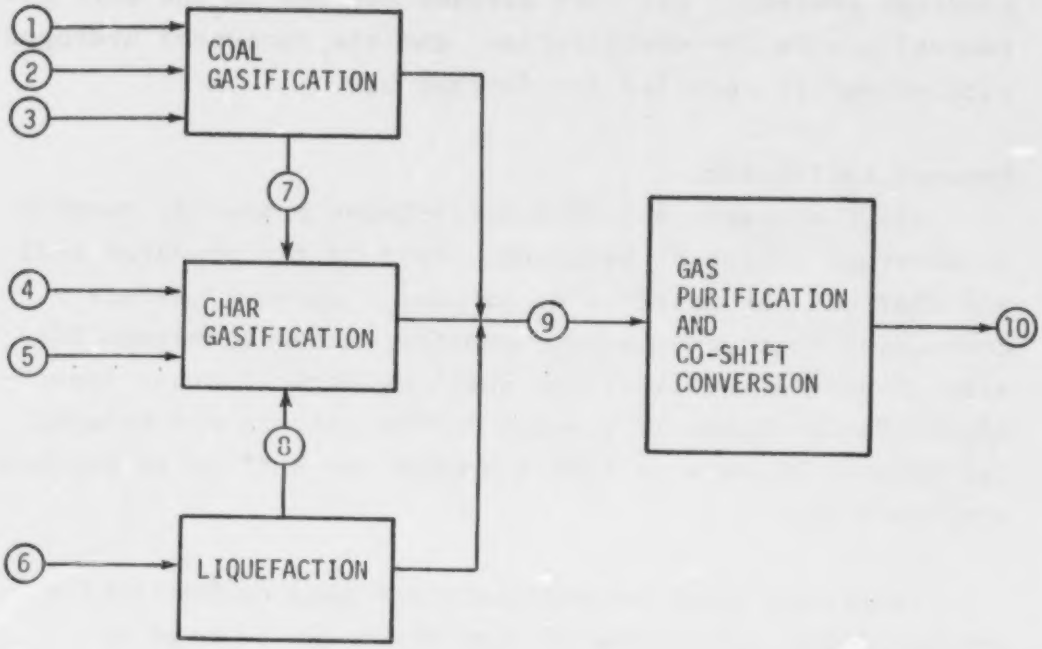
Hydrogen/Synthesis Gas Generation

The need for hydrogen generation in coal liquefaction arises from the fact that the ratio of hydrogen to carbon in coal, which is about 1:(15-20), has to be raised to about 1:(6-10) to obtain liquid fuels. Generally speaking, 400 to 600 m^3 hydrogen is required to process one metric ton of coal to liquid fuels. Hydrogen is used in liquefaction processes in the following modules:

- Hydrogenation
- Hydrocarbonization
- Hydrotreating

Hydrogen is generated from the gasification of coal, carbon residues, and/or char, and is recovered from gases generated during liquefaction. Hydrogen generation and its end uses are shown in Figure 44.

Coal is gasified with steam and air. Vapors from the gasifier are purified to remove acid gases. The remaining gas, mainly a mixture of CO and H_2, is used as a recycled hydrogen-rich stream to any of the three hydrogen-using modules mentioned. For further details on the hydrogen/syngas generation operation, Reference 25 should be consulted.



1
2
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COAL GASIFICATION
7
4
5
CHAR GASIFICATION
8
6
LIQUEFACTION
9
GAS PURIFICATION AND CO-SHIFT CONVERSION
10

1. COAL
2. AIR OR OXYGEN
3. STEAM
4. OXYGEN
5. STEAM
6. COAL SLURRY
7. CHAR
8. CHAR
9. REACTION GASES
10. HYDROGEN RICH-GAS TO HYDROGENATION, HYDROTREATING, HYDROCARBONIZATION OR CATALYTIC SYNTHESIS

Figure 44. Hydrogen/synthesis gas generation

Gases discharged from some modules, such as hydrogenation, separation, and hydrotreating, have a significant hydrogen content. All such streams are fed to the acid gas removal module for purification, and the recovered hydrogen-rich stream is recycled for further use.

Process Application--

All hydrogenation and donor solvent processes require an external source of hydrogen. Part of the prepared coal and char will be gasified to produce a gaseous mixture containing hydrogen, carbon monoxide, methane, carbon dioxide, hydrogen, sulfide, and small amounts of other impurities. Particulates if present in the mixture are removed. The gaseous mixture is then quenched and shifted to produce synthesis gas.

Processes based on pyrolysis and hydrocarbonization produce large quantities of char which can be used to produce synthesis gas, as described above. Additional coal may or may not be necessary to meet hydrogen requirements for these processes.

Hydrogen-rich gases recovered from the acid gas removal module provide part of the hydrogen required in all but the supercritical gas extraction process. This process uses hydrogen, however, to hydrorefine the products.

Materials Entering--

- Char
- Air
- Oxygen
- Acid gases
- Coal

Equipment--

The type of equipment used for hydrogen generation will depend on many factors. Hydrogenation and donor solvent processes produce solid residues which contain unreacted carbon. However, the amount of residue produced generally will not be sufficient to generate the amount of hydrogen consumed by the process. Additional coal will be required. The solid residue cake must be dried, sized and then mixed with coal to make the feed acceptable for first generation gasifiers, such as Lurgi and Winkler. Second generation gasifiers, such as BI-GAS and Texaco gasifiers, are being developed which could possibly accept solid residue feed directly.

All pyrolysis processes produce large amounts of char, a by-product which is utilized to generate hydrogen. Char has to be sized for use in the first generation Koppers-Totzek process. The COGAS fluidized bed gasifier is being developed to gasify char produced in a pyrolysis process.

The following is a list of major equipment required for hydrogen generation.

- Gasifier
- Shift converter
- Acid gas absorber
- Regenerator.

Conditions--

Gasifier operating conditions are shown in Table 3. The CO-shift converter operates at a temperature of 340° to 370°C and a pressure of 1.0 to 9.8 MPa in the presence of iron-chromium oxide catalysts.

TABLE 3. GASIFIER CONDITIONS

Gasifier type	Pressure, MPa	Temperature, °C
Lurgi	2.4 - 3.1	620 - 760
Winkler	0.1 - 0.3	815 - 1010
Koppers-Totzek	0.1	1815
BI-GAS	9.8	925 - 1480
Texaco	2.7	1095 - 1370
COGAS	0.1 - 0.3	870 - 925

Output Streams--

- Process Streams
  - H_2-rich gas (synthesis gas)
- Waste Streams
  - Flue gases containing CO_2 and trace amounts of sulfur compounds in hydrocarbons
  - Wastewater containing phenols, ammonia, tar and oils
  - Purge from acid gas removal
  - Ash.

Oxygen Generation

Air is compressed, cooled and liquefied. The liquefied air is then fractionated. Each component is allowed to boil off or vaporize separately and in this manner oxygen is separated from nitrogen, carbon dioxide, argon and the minor component gases.

Process Application--

Systems to which oxygen generation applies include all of the liquid phase hydrogenation systems except CO-Steam, the Donor Solvent, COED, Coalcon, Fischer-Tropsch and Methanol Synthesis.

Input Streams--

The input requirements are air, steam, cooling water and electric power. Activated carbon and silica gel are also used. Air consists of an invariable mixture of gases, in percent by volume: nitrogen - 78, oxygen - 21, argon - 0.94, hydrogen - 0.01; and small amounts of neon, helium, krypton and xenon. It also contains varying amounts of carbon dioxide (0.03 to 0.07), water vapor (0.01 to 0.02) and hydrocarbon gases such as acetylene and methane, as well as local pollutants.

Conditions--

The pressures of the various cycles range from 0.4 to 214 MPa. The temperatures go down to -190°C.

Equipment--

- Filters
- Compressors
- Heat exchangers
- Activated carbon filters
- Silica-gel dryers
- Turboexpanders
- High-speed turbines
- Electric generators
- Double fractionating columns
- Condenser-reboilers
- Glass cloth filters
- Sub-coolers

Output Streams--

Oxygen of course, is an intermediate product of this module. By-products are nitrogen, neon, helium, argon, krypton, and xenon.

Acid Gas Removal

Most acid gas removal procedures usually involve chemical or physical absorption of the CO_2 and H_2S in a liquid, and then regeneration of the absorbent by desorption of the acid gas at a lower pressure or higher temperature. There are a number of specific processes that are applicable for liquefaction processes. A brief discussion of several of the more common specific processes are discussed below.

Hot Carbonate Process--

Acid gases are absorbed in a solution of potassium carbonate. The solution is regenerated by desorption in a tower at reduced pressure with steam stripping. By modifying the design, two acid gas streams can be obtained, one high in sulfur content which can be used for a feed into a Claus plant, and one high in carbon dioxide. Hydrogen sulfide can be removed from the latter by incineration.

Cold Methanol Process--

All types of sulfur compounds as well as combustibles can be removed by this proprietary process, known as Rectisol. The acid gases are absorbed in methanol at reduced temperatures. One type of Rectisol unit incinerates the acid gas following sulfur removal. In some cases the Rectisol process uses nitrogen as stripping gas and can also be used to remove water from the product gas.

Amine Process--

A process which uses an amine system produces a sufficiently high concentration of H_2S in the sour gas stream for a Claus plant to accept. Although several hundred parts per million of sulfur compounds and most of the CO_2 remain, the gas is acceptable for product gas.

Dimethoxytetraethylene Glycol Process--

This process, also known as Selexol, prepares a rich enough H_2S stream to be used in a sulfur recovery plant, such as Claus. Acid gases are absorbed with dimethoxytetraethylene glycol. The solvent is regenerated by physical desorption.

Process Application--

All coal liquefaction processes require acid gas removal units for purposes of sulfur and carbon dioxide control.

Materials Entering--

Sour gas streams rich in H_2S and CO_2 from product recovery, gasification, etc. are sent to the acid gas removal unit where they are absorbed by a variety of reactants, dependent on the particular gas removal process.

Conditions--

Pressure: 1.5 to 13.8 MPa, depending on process.

Feed Gas Temperature: 0° to 43°C, depending on process.

Equipment--

- Absorber
- Regenerator (stripper, flash drums, etc.)
- Condensers

Output Streams--

Process	Process Streams	Waste Streams
Hot carbonate (the Amine and Selexol processes have similar streams)	Product gas	Process condensate containing phenol, cyanide, ammonia, and sulfides
		CO_2 stream containing H_2, CO, HC, etc. and sulfur compounds
Cold Methanol	Product gas	Process condensate containing phenol, cyanide, ammonia, and sulfides
		Lean H_2S flash gas containing CO_2, hydrocarbons and H_2
		Rich H_2S flash gas containing methanol, CO_2, H_2S, and hydrocarbons
		Expansion gas and CO_2 CO hydrocarbons and H_2

Water Supply

The function of this module is to improve the quality of both raw water and any recycled water to meet the requirements of the coal liquefaction system. Standard water conditioning methods are used.

Process Application--

This module applies to all coal liquefaction systems.

Input Streams--

- Raw water
- Slightly contaminated wastewater

- Treated wastewater
- Treatment chemicals

Conditions--

Ambient conditions are satisfactory for most of the operations in this module.

Equipment--

- Filters
- Tanks
- Pumps
- Chemical feeders
- Electrodialysis
- Clarifiers
- Mixers
- Ion exchangers
- Reverse osmosis
- Deaerators

Output Streams--

- Treated water
- Sludges
- Brines
- Spent regenerant solutions

Water Cooling

The function of this module is to provide for heat release, using evaporation via cooling towers and ponds and/or air cooling.

Process Application--

This module applies to all coal liquefaction systems.

Input Streams--

The major input is heated water from non-contact heat transfer applications in other process and auxiliary modules. Other inputs to this module are chemical additives used to maintain cooling water quality by preventing corrosion and algal growth.

Conditions--

Temperatures may range from near 0° to 100°C and atmospheric pressure.

Equipment--

- Cooling towers, wet or dry
- Spray ponds
- Pumps
- Filters

Output Streams--

- Water
- Blowdown
- Evaporation
- Spray and windage loss

Product Storage

This module provides for storage, handling and loading of products and by-products.

Process Application--

All coal liquefaction systems use this module.

Input Streams--

- Liquefied coal
- Sulfur

- Naphtha
- Light oil
- Heavy oil
- Tar
- Still bottoms
- Phenol

Conditions--

Ambient conditions of temperature and pressure obtain in this module except when certain products may be too viscous to flow at ambient temperature.

Equipment--

- Tanks
- Bins
- Silos
- Pumps
- Heaters

Output Streams--

All of the input streams also appear as output streams. Waste streams include spills of product and by-product materials, fugitive vapor losses, tank cleaning wastes and area drainage.

Sulfur Recovery

The purpose of this module is to trap or recover the sulfur which is separated from the liquefaction products by previous operations, and to prevent the release of sulfur compounds to the atmosphere. The Claus Sulfur Recovery Process with a Stretford Section has become a widely used method for converting hydrogen sulfide gases to elemental sulfur.

Process Application--

This module applies to all coal liquefaction systems.

Input Streams--

The major input stream is an acid gas mixture containing mainly H_2S with some CO_2 and lesser amounts of hydrocarbons, NH_3 and water.

Conditions--

The theoretical flame temperature is about 1370°C. The reaction furnace effluent is about 1295°C.

Equipment--

- Furnaces
- Blowers
- Waste heat boilers
- Catalytic converters
- Coalescers
- Stack/incinerator
- Condensers
- Heaters
- Pumps
- Pits
- Knockout drums

Output Streams--

- Sulfur
- Wastewater
- Exhaust or vent gas containing mainly nitrogen and carbon dioxide with some water vapor, a fractional percent of CO, less than 250 ppm of COS, and lesser amounts of hydrocarbons
- Spent catalyst (cobalt-molybdate)

Wastewater Treatment

The complexity of wastewater streams from coal liquefaction systems requires a broad variety of treatments for control of the potential environmentally significant materials borne by such streams. These requirements include most of the known wastewater treatment systems and new ones yet to be devised. Table 4 lists some of the standard systems under Liquids Treatment.

Almost all modules discharge a wastewater stream. The volume and characteristics of wastewater from each module are process specific but constituents of wastewater are similar for all processes utilizing a specific module. Some wastewater streams may be treated and reused.

Process Application--

This module applies to all coal liquefaction systems.

Input Streams--

Sources and characteristics of some of the input streams to this module are shown in Table 5. Some waste streams will be treated through only part of the whole treatment system depending on the origin of the stream and its characteristics. Wastewater from the coal preparation module is sent to a separate retention pond to permit the settling of suspended solids. Oily waste streams containing high amounts of phenols and ammonia are treated for recovery. Ammonia is recovered by stripping. After the oil is separated, phenols are recovered by solvent extraction. A probable sequence of steps and control operations to clean up sour water is as follows:

TABLE 4. PARTIAL LIST OF CONTROL APPROACHES FOR WASTE TREATMENT (26)

1. Gas treatment
   - Mechanical collection
   - Electrostatic precipitators
   - Filters (fabric, granular, etc.)
   - Liquid scrubbers/contactors
   - Condensers
   - Solid sorbents (mol sieves, activated carbon)
   - Incineration (direct and catalytic)
   - Chemical reaction
2. Liquids treatment
   - Settling, sedimentation
   - Precipitation, flocculation
   - Flotation
   - Centrifugation and filtration
   - Evaporation and concentration
   - Distillation, flashing
   - Liquid-liquid extraction
   - Gas-liquid stripping
   - pH adjustment
   - Biological processes
   - Oxidation processes
   - Activated carbon and other absorbents
   - Ion exchange systems
   - Cooling towers and ponds
   - Chemical reaction and separation
   - Water intake structures
3. Solids treatment
   - Fixation
   - Recovery/utilization
   - Processing/combustion
   - Chemical reaction and separation
   - Oxidation/digestion
   - Physical separation (specific gravity, magnetic, etc.)
4. Final disposal
   - Pond lining
   - Deep well injection
   - Burial and landfill
   - Sealed - contained storage
   - Dilution (water)
   - Dispersion (air, land)
5. Process modifications
   - Feedstock changes
   - Stream recycling
   - Process design improvements
6. Combustion modification
   - Furnace modifications
   - Optimum burner/furnace design
   - Alternate fuels/processes
   - Fuel additives
7. Fuel cleaning
   - Physical separation
   - Chemical refining
   - Carbonization/pyrolysis
   - Treatment of liquid fuels
   - Fuel gas treatment
8. Fugitive emissions control
   - Surface coatings/covers
   - Vegetation
   - Miscellaneous methods of control
   - Leak prevention
   - Vapor recovery systems
   - Ballast water treatment
9. Accidental release technology
   - Spill prevention in storage
   - Spill prevention in transportation
   - Spill prevention in oil & gas production
   - Flares
   - Spill cleanup techniques

TABLE 5. SOURCES AND CHARACTERISTICS OF WASTEWATER STREAMS

Module or process	Source	Wastewater stream	Constituents
Coal pretreatment operation:			
Sizing, drying, pulverizing, and slurrying	Coal storage piles, sizing and drying	Water, runoff and washdown	Suspended particles, dissolved solids
Coal liquefaction operation:			
Hydrogenation	Cooling and quenching	Foul water	Phenols, tars, ammonia, thiocynates, sulfides and chlorides
Pyrolysis/hydrocarbonization	Cooling and quenching	Foul water	Phenols, tars, ammonia, thiocynates, sulfides and chlorides
Extraction	Char quenching	Foul water	Phenols, tars, ammonia, thiocynates, sulfides and chlorides
Catalytic synthesis	Condensing	Condensate	Phenols, ammonia, sulfides
Separation operation:			
Flashing & condensing	Condensation	Process condensate	Oils, HC, phenols, NH_3 & sulfides
Filtration	Condensation	Process condensate	Oils, HC, phenols, NH_3 & sulfides
Centrifugation	Condensation	Process condensate	Oils, HC, phenols, NH_3 & sulfides
Solvent de-ashing	Condensation	Process condensate	Oils, HC, phenols, NH_3 & sulfides
Vacuum distillation	Condensation	Process condensate	Oils, HC, phenols, NH_3 & sulfides
Coking	Condensation	Process condensate	Oils, HC, phenols, NH_3 & sulfides
Quenching	Quench	Foul water	Oils, HC, phenols, NH_3 & sulfides
Oil-water separation	Quench	Foul water	Oils, HC, phenols, NH_3 & sulfides
Purification/upgrading operation:			
Fractionation	Condensing	Condensate	Light hydrocarbons, dissolved salts
Hydrotreating	Condensing	Condensate	Phenols, ammonia, sulfides
Auxiliary processes:			
Hydrogen/syngas generation	Cooling and quenching	Foul water	Phenols, tars, ammonia, thiocyanates, sulfides and chlorides
	CO-shift	Water	Phenols, tars, ammonia, thiocyanates, sulfides and chlorides
Oxygen generation		Cooling water	Dissolved solids, suspended solids
Acid gas removal	Adsorption and regeneration	Purge flows	Dissolved sulfides in gas removal solvent
Water supply	Treatment	Sludges	DS, SS, HC
Water cooling	Towers, ponds	Blowdown, sludges	DS, SS
Product storage	Leaks, washdown	Wash water	HC
Sulfur recovery	Washdown	Wash water	Sulfur
Wastewater treatment	All steps	Sludges	DS, SS, HC
Gaseous waste treatment	Scrubbers	Scrub water	DS, SS, HC
Solid waste treatment	Leaching	Leachate	DS, HC
Particulate recovery	Scrubbers	Scrub water	Coal, ash
Miscellaneous by-product recovery	Separation	Foul water	Oils, HC, phenols, NH_3 & sulfides
Steam and power generation	Fuel combustion	Blowdown, ash-water	OS, SS, ash
Transient waste treatment	Spills, leaks, washdown	Wash water	DS, SS, HC, ash, coal

- Removal of H_2S, NH_3, CO_2, and light gases:
  - Stripper

- Initial oil and solids removal:
  - API separators
  - Baffle plate separators

- Further oil and solids removal:
  - Clarifiers
  - Dissolved air flotation
  - Filters

- Organic waste removal:
  - Activated sludge
  - Aerated lagoons
  - Oxidation ponds
  - Trickling filters
  - Activated carbon
  - Combination.

Conditions--

Most of the treatments are applied at ambient conditions of temperature and pressure. Others like oxidation, extraction and stripping involve higher temperatures and some may involve reduced pressures.

Equipment--

Reference is made to Table 4 which suggests the types of equipment used in this module. Additional details are being compiled in a document, The Multimedia Environmental Control Engineering Handbook.

Output Streams--

- Treated water
- Sludges

- Oils
- Tars
- Organics

Gaseous Waste Treatment

This module provides for treatment of vent gases and exhausts from all other modules. Some of the methods used are: oxidation, absorption, adsorption, and precipitation. Table 4 lists additional methods.

Process Application--

This module is applicable to all coal liquefaction systems.

Input Streams--

Inputs to this module will consist of mixtures of gases containing:

- Flue gas
- Hydrocarbon vapors
- Oxides of sulfur, carbon and nitrogen
- Sulfides
- Ammonia
- Particulates
- Ash
- Trace elements and compounds

Table 6 lists some of the sources of these emissions. Table 7 indicates the capabilities of particular control equipment.

TABLE 6. SOURCES AND CHARACTERISTICS OF AIR EMISSIONS

Module	Source	Emissions
Coal pretreatment operation:		
Sizing, drying, pulverizing and slurrying	Vents and exhausts	Particulates, hydrocarbon vapors
Coal liquefaction operation:		
Hydrogenation	Preheater flue gas	CO, NO_x, hydrocarbons
Pyrolysis and hydrocarbonization	Preheater flue gas	CO, NO_x, hydrocarbons
Extraction	Vapor leaks	CO, NO_x, HC
Catalytic synthesis	Heater flue gas	CO, NO_x, hydrocarbons
Separation operation:		
Flashing & condensing	Flash drum vapors	Hydrocarbons, sulfides, sulfur dioxide, ammonia, particulates
Filtration	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Centrifugation	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Solvent de-ashing	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Vacuum distillation	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Coking	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Quenching	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Oil-water separation	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Purification/upgrading operation:		
Fractionation	Uncondensed gases from condenser	H_2S, CO_2
Hydrotreating	Preheater flue gas catalyst removal and replacement	CO, NO_x, H_2S, NH_3, hydrocarbons, particulates
Auxiliary processes:		
Hydrogen/syngas generation	Acid gas CO_2 steam driers flue gas	CO_2, CO, hydrocarbons, sulfides, CO, NO_x, H_2S, NH_3
Oxygen generation	Air separation	Nitrogen
Acid gas removal	CO_2 gas stream	CO_2, H_2S, CO, hydrocarbons, sulfides
Water cooling	Tower drift	Spray, biocides anticorrosives
Product storage	Evaporation and leaks	Hydrocarbon vapors
Sulfur recovery	Tail gas vent	SO_2, COS
Wastewater treatment	Separations	Hydrocarbon vapors, NH_3
Gaseous waste treatment	Separation, combustion	SO_x, NO_x, COS, CO, hydrocarbon vapors
Solid waste treatment	Landfills, handling	Hydrocarbon vapors, particulates, SO_2
Particulate recovery	Separations	Coal and ash particulates
Miscellaneous by-product recovery	Evaporation & gas liberation	HC, H_2S, SO_2, NH_3
Steam and power generation	Fuel combustion products	Flyash, NO_x, SO_x, flue gas
Transient waste treatment	Spills, leaks, fugitive emissions, etc.	All of the above

TABLE 7. EMISSIONS AFFECTED BY AIR POLLUTION CONTROL EQUIPMENT

CONTROL EQUIPMENT EMISSIONS	Dry inertial separators	Electrostatic precipitator	Bag filters	Wet scrubbers (water)	SO_2 scrubbers	NO_x controls	Flares	Cooling tower demisters	Sulfur recovery equipment
Particulates	X	X	X	X	Y	*	*	X	*
NO_x	*	*	*	Y	*	X	*	*	*
H_2S	*	*	*	Y	Y	Y	*	*	X
NH_3	*	*	*	Y	Y	*	X	*	*
Hydrocarbons	*	*	*	Y	Y	Y	X	*	*
CO	*	*	*	Y	*	*	X	*	*
Biocides	*	*	*	*	*	*	Y	X	*
Anticorrosive additives	*	*	*	*	*	*	*	X	*
SO_x	*	*	*	Y	X	*	*	*	*

X = Primary pollutant controlled
Y = Other pollutants controlled
* = Does not reduce emission

Conditions--

Temperature conditions cover the range from ambient to flame temperatures. Pressure conditions are generally ambient or slightly negative.

Equipment--

Table 4 suggests the type of equipment used in this module. Additional details are being compiled in the document, The Multimedia Environmental Control Engineering Handbook.

Output Streams--

- Wastewater
- Sludges
- Air and other gaseous mixtures having reduced concentrations of the input materials
- Solid wastes

Solid Waste Treatment

All modules discharge some solid waste, see Table 8. Methods used for solids treatment are included in Table 4.

Process Application--

Solid waste control applies to all coal liquefaction systems.

Input Streams--

- Coal, particulates
- Ash
- Slag
- Char
- Filter cake
- Still bottoms

TABLE 8. SOURCES AND CHARACTERISTICS OF SOLID WASTES

Module or process	Source	Solid waste
Coal pretreatment operation:		
Sizing, drying, pulverizing, and slurrying	Storage piles, sizing and pulverizing	Particulate coal
Coal liquefaction operation:		
Hydrogenation	Reaction, wastes and catalyst disposal	Particulate coal, ash, slag, mineral matter, char
Pyrolysis/hydrocarbonization	Reaction wastes	Particulate coal, ash, slag, mineral matter, char
Extraction	Reaction wastes	Ash, slag, mineral matter
Catalytic synthesis	Reaction wastes and catalyst disposal	Particulate coal, spent catalyst, ash, slag, mineral matter, char, spent absorbent
Separation operation:		
Flashing & condensing	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Filtration	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Centrifugation	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Solvent de-ashing	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Vacuum distillation	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Coking	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Quenching	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Oil-water separation	Raw liquefaction mixture	Particulate coal, ash, slag, mineral matter, char
Purification/upgrading operation:		
Fractionation	Vacuum tower bottoms	Particulate coal, ash, slag, mineral matter, char
Hydrotreating	Catalyst disposal	Spent catalyst
Auxiliary processes:		
Hydrogen/syngas generation	Feed preparation, gasification, shift	Particulate coal, spent catalyst, ash, slag, mineral matter, char
Acid gas removal	Absorbent disposal	Spent absorbent
Water supply	Treatment	Blowdown, sludges, spent regenerants
Water cooling	Treatment	Blowdown, sludges, spent regenerants
Product storage	Tank bottoms	HC residues
Sulfur recovery	Catalyst	Sulfur
Wastewater treatment	Solids collection	Spent absorbent, blowdown, sludges, spent regenerant
Gaseous waste treatment	Solids collection	Particulate coal, spent catalyst, ash, slag, mineral matter, char, spent absorbent, blowdown, sludges, spent regenerants
Solid waste treatment	Solids collection	Particulate coal, spent catalyst, ash, slag, mineral matter, char, spent absorbent, blowdown, sludges, spent regenerants, sulfur
Particulate recovery	Solids collection	Particulate coal, ash, slag, mineral matter, char, blowdown sludges, spent regenerants
Miscellaneous by-product recovery	Solids collection	HC residues
Steam and power generation	Coal preparation, ash disposal, blowdown	Particulate coal, ash, slag, mineral matter, blowdown, sludges, spent regenerants
Transient waste treatment	Spills, leaks	Particulate coal, spent catalyst, ash, slag, mineral matter, char, spent absorbent, blowdown, sludges, spent regenerants, sulfur

- Trace elements
- Spent catalyst
- Spent absorbents
- Sludges from water treatment and flue gas desulfurization

Conditions--

Treatment methods, see Table 4, determine the conditions under which activities in this module will occur.

Equipment--

- Kilns
- Roasters
- Incinerators
- Digestors
- Classifiers

Additional types of equipment are suggested by Table 4.

Output Streams--

- Wastewater
- Stabilized solids
- Waste gases
- Reclaimed coal
- Reclaimed char
- Regenerated catalyst
- Regenerated absorbents
- Recovered by-products

Particulate Recovery

The function of this module is the collection of coal and ash particulates to prevent their release to the atmosphere, and to recover carbon values.

Process Application--

This module applies to all coal liquefaction systems.

Input Streams--

Vents and discharges from coal sizing, drying, pulverizing, and from coal feeding steps provide the largest input. Water may be an input.

Conditions--

Ambient conditions of temperature at slight negative pressures usually obtain.

Equipment--

- Baghouses
- Filters
- Electrostatic precipitators
- Blowers
- Scrubbers
- Pumps
- Decanters

Output Streams--

- Coal
- Ash
- Vent gas
- Air
- Wastewater

Miscellaneous By-product Recovery

This auxiliary provides for the treatment of waste streams for the removal and collection of recoverable by-products. Some of the methods used are: refinery techniques, air stripping, steam stripping, ion-exchange, break-point chlorination, hydrotreating and solvent extraction.

Process Application--

By-product recovery is applicable to all coal liquefaction systems.

Input Streams--

Feed streams to by-product recovery will consist of mixtures containing materials from the following list:

- Ammonia
- Phenols
- Benzenes
- Naphtha
- Gasoline
- High-, low-, and intermediate Btu gas
- Hydrocarbons
- Ethylene
- Char, coke
- Ash/slag
- Tars (tar acids and tar bases)
- Water

Conditions--

It is apparent from the list of by-products and the methods used for their recovery that a wide range of temperature and pressure conditions will be involved.

Equipment--

Table 4 suggests the type of equipment that might be required for by-product recovery. Additional details are being compiled in a document, The Multimedia Environmental Control Engineering Handbook.

Output Streams--

- Wastewater
- Sludges
- Non-condensible gases
- Ammonia
- Phenols
- Benzenes
- Gasoline
- Hydrocarbons
- High-, low- and intermediate Btu gas
- Char, coke
- Ash/slag
- Tar (tar acids and bases)
- Naphtha
- Ethylene

Steam and Electric Power Generation

In this module the chemical energy of some form of fossil fuel, probably coal, is transformed into steam and electric energy to meet the requirements of all other modules in the plant. Present day methods of utilizing the energy of fossil fuel are based on a combustion process, followed by steam generation to convert the heat first into mechanical energy and then to convert the mechanical energy into electrical energy.

Process Application--

This module applies to all coal liquefaction systems.

Input Streams--

Coal, fuel oil, and natural gas can all be used as fuels, however, coal will probably be used. The other main input stream is water. Additional inputs are treatment chemicals for raw water and for waste treatment.

Conditions--

Conditions will depend on the characteristics of the steam and electric power requirements of the coal liquefaction systems.

Equipment--

- Boilers
- Turbine generators
- Condensers
- Pumps
- Scrubbers
- Dearators
- Precipitators
- Ash handling systems

Output Streams--

- Boiler blowdown
- Fly ash
- Bottom ash
- Ash sluice water
- Floor drains
- Flue gas
- Contaminated floor and yard drains
- Intake screen backwash
- Cleaning wastes

Transient Waste Treatment

Waste streams produced during normal process operation are expected and provisions are made for their continuous disposition. Consideration must be given to waste streams generated as a result of intermittent occurrences. Such releases have been termed transient pollutants. These releases may be unplanned or accidental; they can be caused by leaks, spills, upsets, startups, shutdowns, power failures, process equipment failures, slugging, surging, and overloading. They may also be caused by or occur during maintenance operations. Because of their nature, such releases are difficult to sample, analyze, and classify. However, if some thought is given to possible situations, it is more likely that the impact of fugitive emissions can be minimized. In many cases, the best disposition of the unwanted stream is to return it to the process.

Spills and leaks will occur and provisions for cleanup and containment should be made. Pumps and valves are known sources of leaks. Solids handling equipment also can cause problems. Belt conveyors or bucket elevators can break or jam causing spills or fires. In such cases, it may be necessary to dump materials and make repairs to resume normal operations. Vacuum cleanup trucks could reclaim these spilled solids for reuse. Water flushing can wash residual solids and flush oil spills to an "oily water" sewer system for recovery.

During startup, shutdown, or a plant upset, off specification products may be made. Rather than dispose these materials through the waste treatment facilities, it will probably be much more desirable to store them and rework them into the proper specifications. This procedure, however, will require adequate storage. Enclosed storage will be needed for many of the liquids removed at shutdown. Vapors, particularly odors, may be released. Water layers from separations will contain various sulfur, nitrogen, and oxygen compounds that should not be allowed to escape to the atmosphere. These liquids can be stored until a subsequent startup and used for recharge or they can be worked off through the wastewater treating systems.

Before maintenance is performed the equipment or system will have to be purged to remove toxic and combustible gases. Purged gases should be sent to an incinerator or furnace. This procedure also applies to shutdowns. Certain catalysts or carbonaceous materials may be pyrophoric at high temperatures. Inert gas purge and cooling will be required to prevent fire.

In the case of plugging it may be necessary to flush the system with a light oil or with water. Provision must be made to collect and store the cleaning stream until it can be either recycled or treated for disposal. Slugs of liquids resulting from upsets or surges may be sent to the flare. Serious fires or explosions could be caused if separators are not sized to prevent entrainment.

Inspection, monitoring, and maintenance programs are essential to controlling transient pollutants.

Process Application--

This module applies to all liquefaction systems.

Input Streams--

Material inputs to this module include those listed above for all other modules.

Conditions--

Conditions for transient pollutant control are determined by the pollutant and the treatment to which it is subjected. Conditions will correspond to those of the above control modules or to a process or operation in the case of materials returned to processing.

Equipment--

Equipment needs for this module correspond to those identified for each module and, in addition, fire fighting and specialized materials handling equipment such as vacuum cleanup systems.

Output Streams--

Outputs will correspond also to those of the control module in which the transient pollutant is treated.

SECTION 3

ENVIRONMENTAL ASSESSMENT REQUIREMENTS

INTRODUCTION

The purpose of this section is to assess the known information and to determine criteria for selecting proper control technologies to limit pollutant discharges. Table 4, Section 2, provides a listing of most of the available approaches to control technologies.

Initially the types of pollutants probably present in waste streams were determined. This was based on available documentation on liquefaction emissions and consideration of discharges from related industries such as coal-fired power plants and petroleum refineries.

Next, the pollution controls were evaluated to determine each type's capabilities and limitations. Among factors considered were:

- The type of pollutants controlled by the specific technology
- Physical properties of the pollutants that might affect selection of controls
- Chemical properties of the pollutants that might affect selection of controls

- Efficiency of controls

- Contaminants in the waste stream that could limit or prevent use of a specific type of control

- The local environment including climate, water availability, and soil characteristics.

When possible, controls were matched with anticipated effluents. Specific determinants of the best suited technology were noted. The following discussion on air, water, and solid waste controls is based upon this procedure. Further, more detailed studies are being conducted. This is a repetitive process due to changing waste stream and control technology characterization.

SELECTION OF SUITABLE AIR POLLUTION CONTROLS

It is well recognized that no uniform gas cleaning method exists that will satisfy all problems and conditions. In the selection of proper control technologies, both physical and chemical properties must be considered. The degree of efficiency of different control options also must be a basis for selection.

For example, in particulate control, coarse dust particles are separated by dry inertial separators whereas fine dusts require the use of fabric filters, scrubbers, or electrostatic precipitators. To meet a specific level of emission, highly efficient removal systems such as precipitators are required for controlling streams with large amounts of fine particulates. Cyclones might be applicable for removal of less concentrated coarse particles. Particulate properties which are basic to the performance and selection of gas cleaning equipment are particle size distribution, structure, density, composition, electrical conductivity and agglomeration tendencies. Also, gas properties such as temperature, moisture content, total gas flow, and chemical composition must be considered. For example, particulate removal efficiency for precipitators increases as sulfur content in the waste stream exceeds two percent. Fine particulates will probably need a better control than now exists.

Sulfur dioxide controls are not now necessary with coal-fired boilers smaller than 264 GJ/hr. This, however, should be evaluated.

The use of flares to control hydrocarbon emissions is primarily dependent on the availability of sufficient waste gases to maintain combustion.

Sulfur-recovery process selection is limited by the composition of the acid-gas feed stream. When the Stretford process is operated on fuel gas, the concentration of sodium thiosulfate builds up in the circulating solution and must be purged. Other contaminants to the solution include HCN, SO_2, ammonia, and heavy hydrocarbons. Stretford cannot be used alone if significant amounts of organic sulfur are present. Most mercapatans, carbonyl sulfides, and carbon dioxide pass through the absorber into the exit gas. To maintain Claus process efficiency, on the other hand, requires a minimum concentration of approximately ten to fifteen volume percent of H_2S. High levels of CO_2 water vapor and hydrocarbons in the acid gas feed also reduce the efficiency.

Availability of water also can determine which control should be selected. In arid regions, dry methods of controlling emissions must be considered.

Detailed analyses of waste stream composition and concentration combined with aforementioned properties of air pollution controls are needed to provide adequate data to select the proper control system.

SELECTION OF SUITABLE WATER POLLUTION CONTROLS

All process wastewater streams mentioned in Section 2 have different characteristics. The selection of the best control technology will depend on the information available for each stream.

The compounds of interest can be divided into classes such as dissolved gases, organics, trace elements, phenols, and sulfur and nitrogen compounds. Knowledge concerning characteristics such as BOD, COD, TOC, suspended solids, pH, and oil and grease is also essential. Table 9 shows some of the individual compounds of each class that may be present.

It may be that two or more wastewater streams can be treated by a common method. The variation in characteristics of wastewater streams and capability of control systems to handle such variations can be evaluated by changes in the feedstock and operating variables. The concentration levels of recoverable compounds such as ammonia and phenols will determine the feasibility of recovery. Combination physical/chemical methods may remove some materials such as phenols. The performance of biological oxidation systems in the presence of toxic metals is not fully known and requires evaluation.

TABLE 9. SOME CHARACTERISTICS OF WASTEWATER

Component	Class	Item or property of interest
Dissolved gases	Inorganic	O_2, NH_3, CO, SO_x, HCl, HCN, HF, H_2S, CS_2
	Organic	CH_4, C_2H_6, C_2H_4, CH_3SH, C_2H_5SH
	Sulfurous	COS, CS_2, CH_3SH, C_2H_5SH
Organic liquids and solids	Polynuclear aromatic compounds	Pyrenes, fluorenes, benzopyrenes, phenanthrenes, fluoranthenes, chrysenes
	Nitrogen compounds	Pyridine, quinoline, indole, carbazole, acridine
	Phenols	Phenol, cresols, xylenols, naphthols
	Sulfur compounds	Mercaptans, thiophenol, thiocresol, benzothiophenes
Trace elements		Ba, Be, Ca, Cr, Cu, Mn, Mo, Ni, Sr, V, Zn, As, B, Cd, F, Hg, Pb, Sb, Se, Sn
Ions		$S^=$, $SO_4^=$, NO_3^-, F^-, Cl^-, Br^-, CN^-, PO_4^-, $CO_3^=$, HCO_3^-, SCN^-
Gross characteristics		BOD, COD, TOC, suspended solids, oil and grease, specific conductance

Wastewater treatment will generate sludges requiring proper disposal. Sludge characteristics depend on the type of wastewater and will determine the treatment method applied. It is important to identify hazardous materials that may be leached by groundwater. The volume and type of sludge will determine the disposal method that can be used. Sludge with high water content may require pretreatment such as dewatering if it is to be treated as a solid waste. The presence of toxic materials must be assessed and positive indications will make it necessary to find control means for preventing their entry into the environment.

The complete wastewater control system will be a combination of physical, chemical, and biological treatment processes. The combination sequence of the individual treatment processes will affect the degree of contaminant removal. Table 10 shows the important characteristics of wastewaters that could influence the choice of wastewater treatment and control systems.

SELECTION OF SUITABLE SOLID WASTE CONTROLS

The bulk solid waste to be landfilled includes various constituent materials. Ash consists of a variety of metallic oxides and trace element compounds. Coal and char particles contain organic and mineral materials. Elemental sulfur may be generated as solid waste from hydrogen sulfide control technologies. Limestone sludges, primarily calcium sulfite and calcium sulfate also may be generated. Zinc sulfide, the primary constituent of spent sulfur guard reactor absorbents, also may be present as will spent catalyst from applicable processes. Wastewater treatment sludges, a mixture of coal tar residues, sand, coal fines, and treatment by-products may also contain untreated quantities of

TABLE 10. WASTEWATER CONTROL SYSTEMS

Important wastewater characteristics	Control method
Flow variability	Equalization
Extreme pH values	Neutralization
Extreme pH values	Temperature adjustment
Nutrient deficiency	Nutrient additions
Settleable suspended solids	Sedimentation
Oils, tars, suspended solids, and other flotative matter	Dissolved air-flotation
Organic content	Activated sludge
Organic content	Aerated lagoon
Organic content	Oxidation pond
Organic content	Trickling filter
Dissolved solids, colloids, metals or precipitable organics, and emulsified oils	Chemical mixing flocculation and clarification
Oils, colloids, tar, and chemically coalesced materials	Dissolved air-flotation with chemicals
Trace amounts of organics and color, taste, and odor producing compounds	Activated carbon absorption
Dissolved gases, variable organics and materials that can be chemically converted to gases	Stripping

phenols, ammonia, cyanides, and other potentially dangerous materials.

Limited knowledge of solid waste component materials restricts the depth to which this subject may be analyzed. Chemical analysis will identify the specific composition of solid waste materials and determine their concentration. It may be necessary to determine the environmental impacts of some materials. In effect, all leachable materials present in concentrations exceeding environmentally acceptable standards should be identified.

Solid waste disposal methods should be designed to permit minimum environmental degradation. Little is known about the fate of landfilled trace elements, spent catalysts, or spent absorbents. Landfilling and minefilling techniques will have to become more sophisticated to prevent contamination of the surrounding area. Hazardous leachable materials present in solid waste should be identified and studied to determine ways to minimize detrimental environmental effects.

One related problem, a result of groundwater leaching, is the reentry to the environment of undesirable ash constituents. A possible solution is to preclude leaching by using impervious liners to prevent groundwater percolation. Chemical stabilization to render leachable constituents insoluble or inert may be a necessary control method in some instances. A combination of physical and chemical control methods may be the required technique.

Subsidence, the gradual settling of landfill materials, is another problem. In some cases, waste compaction reduces subsidence effects, allows more waste disposal per unit volume of storage space, and reduces the permeability of landfilled wastes. This method, which reduces leaching problems, is currently under consideration as a means of improving solid waste disposal techniques. More information is needed regarding the subsidence and compaction properties of the bulk solid wastes generated by liquefaction processes.

Although no secondary wastes are anticipated after landfilling, light hydrocarbon gases may be generated due to reaction of organic materials present. Furthermore, combustible materials may generate gases as well as cause underground fires. Unsuspected or undetected materials may undergo groundwater leaching. Periodic sampling and analysis of landfill materials and the surrounding area may be required to determine if secondary wastes are generated. It may be necessary to develop control technology modifications which will prevent the generation of such wastes.

SECTION 4

PLANS AND TIMING FOR DEVELOPMENT

INTRODUCTION

Fourteen processes have been described in this summary. They represent all four technology categories. All stages of development, from laboratory studies to demonstration projects, are similarly represented. Decisions necessary in the course of program execution will influence the rate and final extent of development of each process.

Most of the processes discussed in this document are funded by DOE. In some cases DOE jointly funds an effort either with another agency or with private industry. Several projects, however, are not currently recipients of federal support. In these cases projections of future program/project plans are not available. Current schedules for construction and operation are shown in Table 11.

Two solvent refined coal pilot plants are the only liquefaction plants in operation as of June 1978. An H-Coal pilot plant, now under construction, will not be operational before the third quarter of FY 79.

Brief discussions of the status of each process under development follow.

TABLE 11. COAL LIQUEFACTION DEVELOPMENT SCHEDULE (2,16,27)

Operation	Scale	Time frame FY78	 FY79	 FY80
Coal pretreatment				
Crushing & grinding	PP	———	———	———→
Pulverizing & sizing	PP	———	———	———→
Drying	PP	———	———	———→
Slurrying & preheating	PP	———	———	———→
Coal liquefaction				
Hydrogenation				
Synthoil	PDU	—·—·—		
H-Coal	PDU, PP	- - - -	- - - -	———→
Bergius	PDU	——→		
SRC	PP, DP	———	———	———→
CO-Steam	PDU	———	———	———→
EDS	PDU, PP	–	- - - -	———→
Pyrolysis/hydrocarbonization				
COED	PP - completed			
Coalcon	DP	—·—·—		
Clean coke	PDU	→		
TOSCOAL	*			
ORC	PDU, PP	——→		
Extraction				
SGE	PP		——→ *	
Catalytic synthesis				
Fischer-Tropsch	CP	———	———	———→
Methanol	CP, DP, CP	*		
Separation				
Flashing & condensation	PP	- - - -	- - - -	———→
Filtration	PP	———	———	———→
Centrifugation	PP	———	———	———→
Solvent de-ashing	PP	———	———	———→
Vacuum distillation	PP	———	———	———→
Coking	PDU	——	→	
Quenching	PP	- - - -	- - - -	———→
Oil-water separation	PP	———	———	———→
Purification & upgrading				
Fractionation	PP	———	———	———→
Hydrotreating	PDU, PP	———	———→	——→
Hydrogen/synthesis gas generation	**	**		

(continued)

TABLE 11 (continued)

Operation	Scale	Time frame		
		FY78	FY79	FY80
Auxiliary processes				
Oxygen generation	*			
Acid gas removal	PP	———	———	———→
Water supply	PP	———	———	———→
Water cooling	PP	———	———	———→
Product storage	PP	———	———	———→
Sulfur recovery	PP	———	———	———→
Wastewater treatment	PP	———	———	———→
Gas waste treatment	PP	———	———	———→
Solid waste treatment	PP	———	———	———→
Particulate recovery	PP	———	———	———→
Miscellaneous by-product recovery	PP	———	———	———→
Steam & power generation	PP	———	———	———→
Transient waste treatment	PP	———	———	———→

----- = construction

——— = operation

———•———•——— = re-evaluation

* has not been announced.

**Status and population of low/intermediate Btu gasification systems are available in Reference 25, p. 21 and Appendix C-1.

PP = pilot plant; PDU = process development unit;
CP = commercial plant; DP = demonstration plant

HYDROGENATION

Synthoil

Continued development of the Synthoil process is currently suspended. A process development unit was constructed but no firm plans for its use have been announced.

H-Coal

A process development unit is in operation. Construction of a pilot plant is underway. Operation is planned to begin in FY 80.

Bergius Process

This is the DOE "disposable catalyst" process. Construction of a process development unit is in progress and initial operation is planned for late 1977. No pilot plant plans exist.

Solvent Refined Coal

Two pilot plants are operating. The 5.4-metric ton per day plant at Wilsonville, Alabama will operate through FY77. A decision is to be made as to whether or not to continue operation.

Operation of the 45.4-metric ton per day Fort Lewis, Washington facility is planned to extend into FY81.

In addition, an 1814-metric ton per day demonstration plant is being considered by the Kentucky Center for Energy Research but no schedule is available.

CO-Steam

Construction of a 4.5-kg per hour continuous unit was completed in FY78. It is now being tested.

Donor Solvent

Operation of the Exxon Donor Solvent process development unit is planned through FY82. Current scheduling calls for pilot plant construction to be completed early in FY80 with operation from FY80 through FY82.

PYROLYSIS AND HYDROCARBONIZATION

COED

The COED project has been completed through the pilot plant stage. The pilot plant has been dismantled. No further work is projected for this process.

Coalcon

Although originally planned for near term construction, DOE is considering suspension of the project due to marginal economics and technical problems with fluidized-bed carbonizers. Additional work is proceeding to eliminate scale-up problems involved in fluidized bed and the decision on the fate of this project has not been announced.

Clean Coke

Operation of a process development unit during FY78 is planned. There are no current plans for pilot facilities.

TOSCOAL

This process is not currently funded by DOE. A facility has been tested using coal in past studies but no information on future plans is available.

Garrett (ORC)

Operation of a small PDU is currently funded by DOE.

EXTRACTION

Supercritical Gas Extraction

This process is at such an early stage of development that no plans beyond inception have been announced.

CATALYTIC SYNTHESIS

Fischer-Tropsch

A commercial plant has been operated in South Africa since 1955 and a second commercial plant is under construction there. No concrete plans have been made yet for process development or pilot studies in this country.

Methanol

DOE studies of methanol are directed to its use as a feedstock for catalytic conversion to gasoline.

Synthesis of methanol from synthesis gas is being planned as a commercial venture.

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APPENDICES

A. SI (METRIC) CONVERSION FACTORS
B. SIEVE SERIES
C. SI SERIES

APPENDIX A. SI (METRIC) CONVERSION FACTORS (28)

To Convert From	To	Multiply By
	Acceleration	
ft/s^2	metre per $second^2$ (m/s^2)	3.048-000 E-01
	Area	
Acre (U.S. survey)[12]	$metre^2$ (m^2)	4.046 873 E+03
ft^2	$metre^2$ (m^2)	9.290 304 E-02
in^2	$metre^2$ (m^2)	6.451 600 E-04
yd^2	$metre^2$ (m^2)	8.361 274 E-01
	Energy (Includes Work)	
British thermal unit (mean)	joule (J)	1.055 87 E+03
Calorie (kilogram, mean)	joule (J)	4.190 02 E+03
kilocalorie (mean)	joule (J)	4.190 02 E+03
	Length	
foot	metre (m)	3.048 000 E-01
inch	metre (m)	2.540 000 E-02
yard	metre (m)	9.144 000 E-01
	Mass	
grain	kilogram (kg)	6.479 891 E-05
grain	kilogram (kg)	1.000 000 E-03
pound (lb avoirdupois)	kilogram (kg)	4.535 924 E-01
ton (metric)	kilogram (kg)	1.000 000 E+03
ton (short, 2000 lb)	kilogram (kg)	9.071 847 E+02
	Mass Per Unit Area	
lb/ft^2	kilogram per $metre^2$ (kg/m^2)	4.882 428 E+00

APPENDIX A (continued)

To Convert From	To	Multiply By
	Temperature	
degree Celsius	Kelvin (K)	$t_K = t_{^\circ C} + 273.15$
degree Fahrenheit	degree Celsius	$t_{^\circ C} = (t_{^\circ F} - 32)/1.8$
degree Fahrenheit	Kelvin (K)	$t_K = (t_{^\circ F} + 459.67)/1.8$
degree Rankine	Kelvin (K)	$t_K = t_{^\circ R}/1.8$
Kelvin	degree Celsius	$t_{^\circ C} = t_K - 273.15$
	Velocity (Includes Speed)	
ft/h	metre per second (m/s)	8.466 667 E-05
ft/min	metre per second (m/s)	5.080 000 E-03
ft/s	metre per second (m/s)	3.048 000 E-01
in/s	metre per second (m/s)	2.540 000 E-02
	Viscosity	
centipoise	pascal second (Pa·s)	1.000 000 E-03
centistokes	metre^2 per second (m^2/s)	1.000 000 E-06
poise	pascal second (Pa·s)	1.000 000 E-01
stokes	metre^2 per second (m^2/s)	1.000 000 E-04
	Volume (Includes Capacity)	
acre-foot (U.S. survey)	metre^3 (m^3)	1.233 489 E+03
barrel (oil, 42 gal)	metre^3 (m^3)	1.589 873 E-01
ft^3	metre^3 (m^3)	2.831 685 E-02
gallon (U.S. liquid)	metre^3 (m^3)	3.785 412 E-03
litre*	metre^3 (m^3)	1.000 000 E-03
	Volume Per Unit Time (Includes Flow)	
ft^3/min	metre^3 per second (m^3/s)	4.719 474 E-04
ft^3/s	metre^3 per second (m^3/s)	2.831 685 E-02
gal (U.S. liquid/day)	metre^3 per second (m^3/s)	4.381 264 E-03
gal (U.S. liquid/min)	metre^3 per second (m^3/s)	6.309 020 E-05

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*In 1964 the General Conference on Weights and Measures adopted the name litre as a special name for the cubic decimetre. Prior to this decision the litre differed slightly (previous value, 1.000028 dm^3) and in expression of precision volume measurement this fact must be kept in mind.

APPENDIX A (continued)

To Convert From	To	Multiply By
	Mass Per Unit Length	
lb/ft	kilogram per metre (kg/m)	1.488 164 E+00
lb/in	kilogram per metre (kg/m)	1.785 797 E+01
	Mass Per Unit Time (Includes Flow)	
lb/h	kilogram per second (kg/s)	1.259 979 E-04
lb/min	kilogram per second (kg/s)	7.559 873 E-03
ton (short)/h	kilogram per second (kg/s)	2.519 958 E-01
	Mass Per Unit Volume (Includes Density & Mass Capacity)	
lb/ft^3	kilogram per metre^3 (kg/m^3)	1.601 846 E+01
lb/gal (U.S. liquid)	kilogram per metre^3 (kg/m^3)	1.198 264 E+02
lb/yd^3	kilogram per metre^3 (kg/m^3)	5.932 764 E-01
	Power	
Btu (thermochemical)/h	watt (W)	2.930 711 E-01
Btu (thermochemical)/h	watt (W)	2.928 751 E-01
cal (thermochemical)/min	watt (W)	6.973 333 E-02
cal (thermochemical)/s	watt (W)	4.184 000 E+00
	Pressure or Stress (Force Per Unit Area)	
atmosphere (standard)	pascal (Pa)	1.013 250 E+05
foot of water (39.2°F)	pascal (Pa)	2.988 98 E+03
lbf/ft^2	pascal (Pa)	4.788 026 E+01
lbf/in^2 (psi)	pascal (Pa)	6.894 757 E+03

APPENDIX B. SIEVE SERIES (29)

Sieve designation		Sieve opening		Nominal wire diam.		
Standard	Alternate	mm.	in. (approx. equivalents)	mm.	in. (approx. equivalents	Tyler equivalent designation
107.6 mm.	4.24 in.	107.6	4.24	6.40	0.2520	
101.6 mm.	4 in.**	101.6	4.00	6.30	.2480	
90.5 mm.	3-1/2 in.	90.5	3.50	6.08	.2394	
76.1 mm.	3 in.	76.1	3.00	5.80	.2283	
64.0 mm.	2-1/2 in.	64.0	2.50	5.50	.2165	
53.8 mm.	2.12 in.	53.8	2.12	5.15	.2028	
50.8 mm.	2 in.**	50.8	2.00	5.05	.1988	
45.3 mm.	1-3/4 in.	45.3	1.75	4.85	.1909	
38.1 mm.	1-1/2 in.	38.1	1.50	4.59	.1807	
32.0 mm.	1-1/4 in.	32.0	1.25	4.23	.1665	
26.9 mm.	1.06 in.	26.9	1.06	3.90	.1535	1.050 in.
25.4 mm.	1 in.**	25.4	1.00	3.80	.1496	
22.6 mm.*	7/8 in.	22.6	0.875	3.50	.1378	0.883 in.
19.0 mm.	3/4 in.	19.0	.750	3.30	.1299	.742 in.
16.0 mm.*	5/8 in.	16.0	.625	3.00	.1181	.624 in.
13.5 mm.	0.530 in.	13.5	.530	2.75	.1083	.525 in.
12.7 mm.	1/2 in.**	12.7	.500	2.67	.1051	
11.2 mm.*	7/16 in.	11.2	.438	2.45	.0965	.441 in.
9.51 mm.	3/8 in.	9.51	.375	2.27	.0894	.371 in.
8.00 mm.*	5/16 in.	8.00	.312	2.07	.0815	2-1/2 mesh
6.73 mm.	0.265 in.	6.73	.265	1.87	.0736	3 mesh
6.35 mm.	1/4 in.**	6.35	.250	1.82	.0717	
5.66 mm.*	No. 3-1/2	5.66	.223	1.68	.0661	3-1/2 mesh
4.76 mm.	No. 4	4.76	.187	1.54	.0606	4 mesh
4.00 mm.*	No. 5	4.00	.157	1.37	.0539	5 mesh
3.36 mm.	No. 6	3.36	.132	1.23	.0484	6 mesh
2.83 mm.*	No. 7	2.83	.111	1.10	.0430	7 mesh
2.38 mm.	No. 8	2.38	.0937	1.00	.0394	8 mesh
2.00 mm.*	No. 10	2.00	.0787	0.900	.0354	9 mesh
1.68 mm.	No. 12	1.68	.0661	.810	.0319	10 mesh
1.41 mm.*	No. 14	1.41	.0555	.725	.0285	12 mesh
1.19 mm.	No. 16	1.19	.0469	.650	.0256	14 mesh
1.00 mm.*	No. 18	1.00	.0394	.580	.0228	16 mesh
841 micron	No. 20	0.841	.0331	.510	.0201	20 mesh
707 micron*	No. 25	.707	.0278	.450	.0177	24 mesh
595 micron	No. 30	.595	.0234	.390	.0154	28 mesh
500 micron*	No. 35	.500	.0197	.340	.0134	32 mesh
420 micron	No. 40	.420	.0165	.290	.0114	35 mesh
354 micron*	No. 45	.354	.0139	.247	.0097	42 mesh
297 micron	No. 50	.297	.0117	.215	.0085	48 mesh
250 micron*	No. 60	.250	.0098	.180	.0071	60 mesh
210 micron	No. 70	.210	.0083	.152	.0060	65 mesh
177 micron*	No. 80	.177	.0070	.131	.0052	80 mesh
149 micron	No. 100	.149	.0059	.110	.0043	100 mesh
125 micron*	No. 120	.125	.0049	.091	.0036	115 mesh
105 micron	No. 140	.105	.0041	.076	.0030	150 mesh
88 micron*	No. 170	.088	.0035	.064	.0025	170 mesh
74 micron	No. 200	.074	.0029	.053	.0021	200 mesh
63 micron*	No. 230	.063	.0025	.044	.0017	250 mesh
53 micron	No. 270	.053	.0021	.037	.0015	270 mesh
44 micron*	No. 325	.044	.0017	.030	.0012	325 mesh
37 micron	No. 400	.037	.0015	.025	.0010	400 mesh

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* These sieves correspond to those proposed as an international (I.S.O.) standard. It is recommended that wherever possible these sieves be included in all sieve analysis data or reports intended for international publication.

**These sieves are not in the fourth-root-of-2 series, but they have been included because they are in common usage.

APPENDIX C. SI SERIES (28)

Multiplication factor	Prefix	Symbol
1 000 000 000 000 000 000 = 10^{18}	exa[a]	E
1 000 000 000 000 000 = 10^{15}	peta[a]	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto[b]	h
10 = 10^{1}	deka[b]	da
0.1 = 10^{-1}	deci[b]	d
0.01 = 10^{-2}	centi[b]	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

[a] Adopted by the CGPM in 1975.

[b] To be avoided where possible. See 3.2.2.